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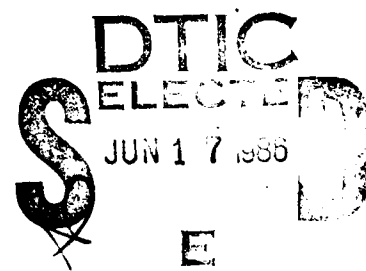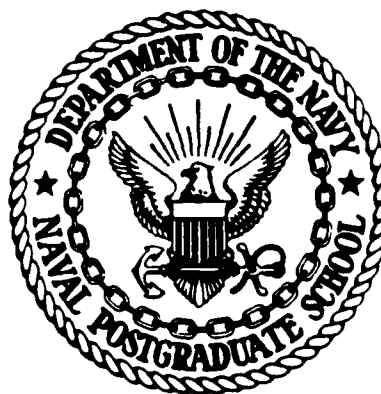
NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

THE GENERALIZED VALUE SYSTEM
AND
FUTURE STATE DECISION MAKING

by

Robert Allen Kilmer

March 1986

Thesis Advisor: Samuel H. Parry

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and
Future State Decision Making

by

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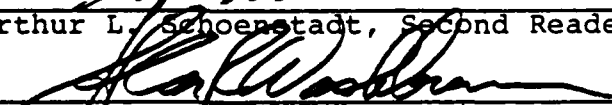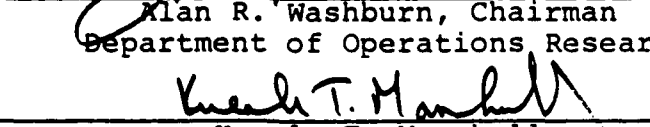Robert Allen Kilmer

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ABSTRACT

This thesis addresses the problem of modeling the decision processes in the Airland Research Model. The Generalized Value System (GVS) is presented as a tool for evaluating the power and value of entities throughout the battlefield at present and future times. Precise definitions and procedures for determining various aspects of power and value are presented. The GVS provides the basis for an approach called future state decision making. An example is given which shows how the approach is used to make decisions at the present time based on what the situation is expected to be in the future.

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I. INTRODUCTION

A. FRAMEWORK OF THE PROBLEM

1. What Is The Problem?

The decision making procedures in existing aggregated combat models are inadequate for modeling the type of warfare that is anticipated by Airland Battle Doctrine. This doctrine indicates that fighting will occur not just within a short distance of the Forward Line of Own Troops (FLOT), but throughout the entire battlefield. In fact, the distinction between forward and rear areas, in terms of the amount and intensity of fighting, will be minimal since it will be difficult or impossible to define battle lines clearly [Ref. 1: p. 1-2]. Existing models have the fight occuring only in areas close to the FLOT. The only way units in the rear areas can be killed in these models is by Air Force interdiction missions. Even though units in rear areas can be destroyed, the effect this has on frontline forces and on the surviving support forces is either ignored or spread evenly over all the forces. Conversely, the effects on support forces in rear areas of destroying a front line unit are also not dealt with in a useful manner. As a result, current models cannot evaluate the strengths and/or weaknesses of the different ways of implementing Airland Battle Doctrine.

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Airland Battle Doctrine is not a fixed, unchangeable, absolute answer as to exactly how U.S. forces should fight. Many articles have been written that are against using this doctrine and many more that suggest improvements to it. Some of these articles appear in an anthology of student papers published in 1984 at the Army War College. (These articles give the opinions only of the individual officers and are not necessarily those of the Army War College.) Two of these articles see the main problem with Airland Battle Doctrine as not having enough fighting capability in our rear areas. [Ref. 2:pp. 68, 242] They point out that when our fighting units go into the enemy's rear area, the enemy will probably have his fighting units come into our rear area so that when our forces return they will find no support units. While both authors agree on the problem, they disagree on how to solve it. One says the solution is to increase the fighting capability of our support units with more combat skills training and better weapons [Ref. 2:p. 68]. The other says the answer is to have a specific light infantry brigade or division designated for rear area protection. [Ref. 2:p. 242] Which approach is correct? If the former is better then how many and what type of weapons should be given to the support units? If the latter is better then what size unit should be used for protection of a corps rear area? Or, is the best answer a combination of the two approaches? This is not the only problem with the Airland Battle Doctrine as proposed in

the August 1982 version of FM 100-5. Two other criticisms

of the doctrine made by a student at the war College are:

- ALBD is not applicable world wide despite its pro-
  ponents claim to the contrary. It is based pri-
  marily on fighting the Soviets in a general war
  in Europe. [Ref. 2:p. 101]

- The value of the doctrine (ALBD) significantly
  decreases if the premise that the Soviets will
  attack in echelon is wrong or if the Soviets dras-
  tically alter their doctrine. [Ref. 2:p. 102]

To respond to such criticisms and to resolve the

problems of how to best implement ALBD will be a difficult

task. It would certainly help if the Army and the Air Force

had techniques that could be used to model such warfare.

The Airland Research Model (ALARM) under development at the

Naval Postgraduate School since January 1985 is an ongoing

attempt to find such techniques.

2. The Goal of the Thesis

The goal of this thesis is to present an approach to

modeling combat that will enable decision making algorithms

to produce logical and consistent military decisions in

battle conditions of the type anticipated in Airland Battle

doctrine. This approach is called "future state decision

making". The foundation of the approach is the Generalized

Value System (GVS), a tool used to determine the "value" or

"worth" of the entities on the battlefield.

3. Roadmap for Achieving this Goal

The following steps will be followed in the GVS

development:

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a. Review the Background of the Airland Research Model

b. Review approaches for determining and using value in existing models

c. Define the terms used in the Generalized Value System

d. Discuss the "future state decision making" approach

e. Analyze the approach using an example

f. Discuss areas requiring additional research/study.

A discussion of existing approaches to the representation and use of value in combat models is given in Chapter II. In Chapter III, the Generalized Value System is described, including precise definitions and examples of its many facets. The actual use of the GVS in future state decision making is illustrated through the use of an actual scenario in Chapter IV. Finally, the salient features of the GVS, as well as directions for future research, are provided in Chapter V.

B. BACKGROUND OF THE AIRLAND RESEARCH MODEL (ALARM)

1. Description

The Airland Research Model is a research effort dedicated to developing new methodologies for modeling large scale warfare of the type anticipated by Airland Battle Doctrine. The three primary purposes of ALARM are:

a. Develop modeling methodology for very large scale and sparsley populated rear areas.

b. Use the methodology in wargaming/simulation with initial emphasis on interdiction.

c. Perform research on Airland Battle concepts. [Ref. 3:p. 2]

ALARM is being developed as a systemic (i.e., no man-in-the-loop) U.S. Corps and Soviet Front level model. It will have the capability of being "opened" up to allow man-in-the-loop decisions during simulations if that is desired.

The model will initially be implemented using the 5th U.S. Corps in Europe for the following reasons. First, the NATO area has been studied extensively and there are accepted "school" solutions for different scenarios. Secondly, there is a considerable amount of risk inherent in this model since several new methodologies are being developed simultaneously. Even though each methodology by itself seems tractable, the main risk involves the interactions between the methodologies. Thirdly, there is a certain amount of risk in implementing Airland Battle Doctrine in any particular environment. It is possible that the ways of implementing the doctrine could be very different for various types of terrain or initial situations. In fact one of the reasons for developing this model is to assist U.S. military tacticians in finding ways to successfully implement Airland Battle Doctrine under different circumstances. However, it is also possible that there are situations in which it will be impossible to determine how to successfully implement the doctrine. While there are differences of opinion on where the doctrine will be applicable, even the most ardent detractors of the doctrine agree that the one place the doctrine would be most likely to succeed is

NATO. So to minimize the probability of failure of the model
due to the doctrine not being applicable, the decision has
been made to initially focus on the NATO scenario.

If the model cannot be made to work in NATO there is
no reason to try it in other places. However, if as is
hoped, it does work in NATO, then there is every intention
of trying the model in other scenarios such as the Middle
East or Southwest Asia. It will then be possible, using the
model, to find the best way of implementing the doctrine in
these areas. At this juncture there does not appear to be
anything in the structure of the methodology proposed in this
thesis that will prevent the methodology from being used in
any particular scenario.

The architecture of ALARM will enable a detailed
audit trail to be established, making it possible to find
cause and effect relationships in battle. This is an essen-
tial feature for modeling decision making. This capability
is arrived at by separating the planning and execution phases
of the model into two distinct modules. A decision made in
the planning module will cause specific results in the execu-
tion module. By running the model again and changing the decision
parameter values, it will be possible to gain insights into
the decision making processes of the model. [Ref. 3:p. 8]

One other major research area in ALARM is network
representations. The objective here is to develop a network

methodology and a multidimensional coordinate system to represent the battlefield environment. The generalized coordinate systems to be developed include:

a. Hierarchical Army unit organization space

b. Combat task force organization space

c. Communications interconnectivity space

d. Transportation interconnectivity space

e. Geometric location in time and space. [Ref.3:p.5]

2. Scope of Thesis Within Alarm

Within a systemic model of war, decision processes have to be developed for each side. It is possible that the processes for each side could be the same, vary slightly, or be completely different. The closer the sides are to each other in terms of military capability, technology, and national objectives, the closer the decision processes will be. Since the U.S. and Soviets are very different in the makeup of their military forces it is likely that their decision processes will also be different. Therefore, it was decided to initially focus on decisions required for Blue defensive missions. Once this has been accomplished the intent is to evaluate the approach and determine if it could be used in making decisions for Blue offensive missions and for Red missions. A cursory evaluation of this sort will be done in this thesis leaving the opportunity for a more detailed effort in the future.

There is one major area of concern that will not be completed in this thesis. That area is the difficult task of providing explicit procedures for obtaining meaningful input data for the variables that will be defined in the thesis. The hope is that this thesis will motivate a continuing effort dedicated to that task.

II.   USES OF VALUE IN COMBAT MODELS

The purpose of this thesis is to show how the GVS can be
used to help make better decisions in the Airland Research
model. Basically what GVS provides is a value for each entity
on the battlefield at any point in time during the battle. It
would be instructive at this point to discuss how existing
models have determined the values of their entities and the
ways that these values have been utilized in the existing
models.

A.   METHODS OF DETERMINING VALUE IN EXISTING MODELS

There are basically two ways of assigning values to enti-
ties on the battlefield. The first is by using the "firepower
score" methodology, which has been used in the ATLAS and
IDAGAM models. The second employs user input values for each
entity as in the STAR model.

1.   Firepower Scores

The firepower score approach has been used in an
attempt to deal with the aggregation problem found in large
force combat models.[Ref. 4:p. 10]   The individual weapon
systems are not represented explicitly but are aggregated or
combined into a larger unit, such as a company or a battalion.
According to the firepower score approach,the value of a unit
depends only on the linearly additive power of its weapons.
It is assumed that it is possible to assign each weapon system

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a firepower score and that the power of a unit, known as the firepower index (FPI), is equal to the sum of the firepower scores of all of the weapons in the unit. Within the context of a battle, the force ratio (FR) is defined as

$$FR = FPI \text{ (Attackers)}/FPI \text{(Defenders)} \; .$$

Obviously the entire procedure is dependent on how "correct" the firepower scores are for each weapon system. Over the years several methods for determining firepower scores have emerged and will be briefly discussed below. [Ref. 5:p. 4-22]

a. Scores Based on Perceived Combat Value.

This method is based on subjective estimates of the relative power of the weapons. Scores are assigned by experts with military experience. [Ref. 5:p. 4-9]

b. Scores Based on Historical Combat Performance

Some work has been done in using actual data from Korea and WWII to determine combat power. The scores are assigned to weapons based on the number of caualties they caused. [Ref. 5:p. 4-9]

c. Scores Based on the Weapons' "Firepower"

This was initially developed for the ATLAS model in the 1960s using data supplied from ballistics research conducted by Army laboratories. For point fire weapons the firepower score equals (Daily ammunition expenditure) x (Probability of a kill). For area fire weapons the firepower score equals (Daily ammunition expenditure) x (Lethal area per round). It is not easy to see how the scores for the two types of weapons are related. [Ref. 4:p. 23]

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d. Scores Based on the Weapons' "Mission
    Dependent Firepower"

This was a refinement to the basic "firepower"
approach that entailed having two firepower scores for each
weapon, one for attack missions and the other for defensive
missions. [Ref. 5:p. 4-9]

e. Scores Based on "Multiple Characteristics
    of the Weapon System"

In this method a weapon's firepower, mobility,
vulnerability, and other characteristics were considered in
determining the weapon's firepower score. In an effort to
indicate that the scores were more than a measure of just the
weapon's firepower, new acronyms were given to the scores.
The individual weapon's score was called the Weapons Effec-
tiveness Index (WEI), and the unit's firepower index was
called the Weighted Unit Value (WUV). A major problem with
methods c, d, and e was that they developed scores which were
measures of performance rather than measures of effectiveness.
[Ref. 5:p. 4-10]

f. Scores Based on the Weapons Killing Ability
    (using linear equations)

The score of a weapon is determined by how effec-
tive the weapon is in eliminating the enemy and in remaining
alive to continue fighting. Specifically, the "value (score)
of a weapon system is directly proportional to the rate at
which it destroys the value of opposing enemy weapon systems".
[Ref. 5:p. 4-22]   This definition can be used to develop a
circular system of eigenvalue equations (which are linear)

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that can be solved to obtain the scores of individual weapons. This is an improvement over the three preceding methods since the score of a weapon depends not only on the characteristics of that weapon but also on the effects that it has on potential targets. This method of computing scores was used in the combat model IDAGAM. [Ref. 5:p. 4-30]

g. Scores Based on the Weapons Killing Ability
   (using nonlinear equations)

This method is very similar to the one used in IDAGAM in that the same type of circular reasoning is used to compute the scores of weapons. The main difference is that it uses a nonlinear importance equation for each weapon. This method is the basis of the ATCAL attrition model. [Ref. 5:p. 6-12] The problem with methods f and g is that the scores are highly dependent on the scenario and cannot be interpreted as long term inherent values.

2. Values Provided by User Input

This method takes the hard question of determining value away from the developer of the model and gives it to the user of the model. In some instances this may be the best thing to do. It certainly should not be rejected as a modeling tool solely because it makes the user provide the inputs. This method is used in the Simulation of Tactical Alternative Responses (STAR) model that was developed in 1979 at the Naval Postgraduate School. STAR is a high resolution, brigade level model in which each weapon system is modeled as a distinct entity. For each weapon system the model maintains a list of

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acquired targets. The user provides different value inputs
for direct and indirect fire weapons. For each type of di-
rect fire weapon, the user provides a table which prioritizes
all possible targets based on the range to the target (in
several range bands) and the type of target. The highest
priority acquired target is selected for engagement. For in-
direct fire weapons a completely different methodology is
used. Three queues are established for indirect fire missions:
counter manuever, counterfire, and SEAD (Suppression of Enemy
Air Defense). For each weapon system type the user provides
input weights for each of the mission queues. As the battle
progresses and targets are identified, the weights increase
in each queue. Within each mission category the indirect fire
weapons prosecute targets according to the priority estab-
lished by the input weights that were assigned to the targets.
[Ref. 6:p. 6-4] The problem with STAR is that there is no
way to compare a direct fire weapon's value for a target with
that of an indirect fire weapon's value for that same target.

Another user input approach to decision making is Multiat-
tribute Utility Theory (MAUT). Several references describing
various aspects of MAUT were reviewed and are listed in the Bib-
liography. The Generalized Value System developed in this thesis
has several characteristics of MAUT such as relating the util-
ity (value) of all factors on a common scale. In addition, both
GVS and MAUT allow for values and objectives to be different
for the various levels of the organization. Additional

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research may indicate other facets of MAUT which may be applicable to GVS.

B. USES OF VALUE IN EXISTING MODELS

1. Firepower Scores Approach

The firepower index is used to describe the condition of a unit at any particular time in the battle. That is, it can give an indication of what is happening to the unit at discrete points in time. The force ratio that is computed from the firepower indices of opposing forces has been used in models for such purposes as:

a. Computing casualties and determining FLOT movement

b. Measuring mission success

c. Determining combat postures such as attack or defense

d. Determining unit priorities for receiving resupply, reinforcement, and air and artillery support

e. Describing the battle situation. [Ref. 5:p. 4-7]

2. User Input Approach -- STAR

Within STAR the values of entities were used to make targeting decisions for individual combat systems. The values could not be used for other decision making purposes. Also they could not be used to give an indication of the status of the battle over time.

C. USES OF VALUE (PROVIDED BY GVS) IN ALARM

At this point in the development of the Airland Research model it is felt that GVS can accomplish all of the things for

which value has been used in the firepower score and STAR
models. In addition, by using GVS in the decision support
system it will enable the model to:

(1) Rank Blue targets and Red targets.

(2) Select Blue assets to engage Red targets.

(3) Determine specific missions for Blue air and
    ground combat, combat support, and combat service
    support units.

(4) Make specific manuever decisions for Blue units.

This is not meant to be the final statement as to what
GVS will enable the model to accomplish. There are probably
other areas that will be identified later that will be
greatly dependent on the GVS. One question that has not been
answered yet is why a value system is essential in ALARM.
The answer to that question lies in the need to be able to
model interdiction, a key part of Airland Battle doctrine.
To model interdiction effectively, a method of evaluating the
importance of each possible target must exist. Finally, it is
hypothesized that the GVS can evaluate the importance of each
target on the battlefield. If this hypothesis is not true,
then GVS will not meet the requirement of being able to model
interdiction. Therefore some other method will have to be
identified. However, if the hypothesis is true, then GVS will
be filling an essential role in ALARM.

III. GENERALIZED VALUE SYSTEM

A. INTRODUCTION

The Generalized Value System was first proposed in 1985 by Professor Art Schoenstadt of the Naval Postgraduate School in an unpublished paper entitled "Toward an Axiomatic Generalized Value System". [Ref. 7:p. 1] It was written from the point of view of trying to rank potential targets by the defending force in ALARM. Several additions and changes have been made to the original Generalized Value System as proposed by Professor Schoenstadt. A major difference is that what was originally called "value" is now "power" which is considered just one component of value.

Each of the words axiomatic, generalized, value, and system, has several different interpretations when used by themselves. The following discussion is an effort to eliminate any misconceptions about what the axiomatic generalized value system is intended to be. The specific interpretations of these words as defined in The Random House College Dictionary are:

(1) Axiomatic - pertaining to principles or rules that have found general acceptance

(2) Generalized - to be made common, shared, or consistent

(3) Value - relative worth, or importance

(4) System - a method or a plan of procedure

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Therefore the axiomatic generalized value system could be described as a common method of determining the importance of "things" based on accepted rules. The "things" that are assigned a value in the model are called entities. The end result of applying this method in a given situation is that the values of entities are comparable. The fact that it is a general or common method indicates that GVS works for all entities in the model. It was pointed out in Chapter 2 that the STAR model had two value systems, one for direct fire weapons and one for indirect fire weapons. The Airland Research model will not have any specialized value systems because the Generalized Value System is capable of describing the value of all entities in the model.

There is another meaning of the word "value" that is used extensively in combat modeling, that being the specific determination of a mathematical quantity or function. [Ref. 8:p. 1453] The value of a function at a specific point is obtained when the function is evaluated at the point (e.g., the value of $f(x)=x^2$ when x=2 is 4). Unless stated otherwise the meaning of the word value, when used in this thesis, is that of the importance or relative worth of an entity.

It may seem that a disproportionate amount of effort has been expended in trying to specify the exact meaning of words that are used in this thesis. The following statement by Captain (Ret.) Wayne Hughes, USN, current president of MORS (Military Operations Research Society) is offered to dispute that contention.

The terminology and dimensionality of warfare are a
mess. We use the terminology of physics all the time:
power, energy, momentum, mass, force, and so forth but
we use them in a chaotic, undisciplined way that is
inexcusable. [Ref. 9:p. 14]

For an extended discussion of the current and past meanings

of the word "value" see Appendix A.

B. ASSUMPTIONS OF GVS

The following assumptions have been made in the General-

ized Value System:

(1) The value of an entity at a particular point in time

to a given hierarchical level is dependent on two factors.

First, value depends on how useful the entity is, at that

time, to that level, with power being the measure of the use-

fulness of an entity. Secondly, value depends on the supply

or availability of the entity.

(2) There are two types of power that an entity might have,

inherent and/or derived. Inherent power is the ability to

disrupt, delay, or destroy the power of enemy entities. De-

rived power is the ability to increase or maintain the inher-

ent power or the derived power of other friendly entities.

Power is measured in STAPOWS (Standard Power units).

(3) The power of an entity that is not ready to execute

its assigned mission is a discounted version of the power of

that entity if it was ready to execute the mission. Thus the

power of an uncommitted unit or of unused support behaves

like a financial asset in the bank—it increases exponentially

with time (as it gets closer to being able to be used).

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(4) As a first order approximation, the value of an entity is equal to its power. For the purposes of this thesis, the consideration of the availability or supply of an entity in determining value will be done only for the Blue side.

(5) One STAVAL (Standard Value) at the beginning of a battle is equal to one STAVAL at the end. The STAVAL is the measure of value in GVS just as the dollar is the measure of value in the economy. Because of inflation the value of a dollar changes from year to year. A dollar in 1960 is worth more than a dollar in 1980. Dollars that have the effects of inflation considered are called nominal dollars. Adjusting nominal dollars so that the effects of inflation are removed produces real dollars. A real dollar in 1960 is worth the same as a real dollar in 1980. Thus the value (and power) of entities in GVS are given in real terms as opposed to nominal terms.

C. DEFINITIONS

This section introduces the terminology and notation that will be used in the GVS.

1. Object

Definition: An object is anything that is explicitly represented in the model.

2. Entity

Definition: An entity is an object that is assigned power (and possibly value).

For the purposes of this thesis the notation used for entities is X1,X2,... for Blue, Y1,Y2,... for Red, and Z1,Z2,... for all entities that cannot be classified as being strictly Red or Blue entities. The following is a list of items that might be considered as entities in the GVS:

(1) Combat, combat support, combat service support ground and air units

(2) Military supplies, transportaion networks (arcs and nodes)

(3) Minefields, obstacles, cities, towns, key terrain features

(4) Dams, power stations, civilian communication and transportation means, defense related industries, food and water supplies

(5) Information

(6) Civilian population, refuges, prisoners of war, national monuments, historical sites, churches and civilian hospitals.

Certainly all of these could possibly be considered valuable or important to a commander during an actual war. Which of these items will be included within GVS will depend on two factors. First, it must be explicitly modeled in ALARM (i.e., it must be an object). Secondly, there must exist a method to determine its power. If these two requirements cannot be met then the item will not be considered an entity.

3. State

Definition: The state $\underline{SX1}(t)$ of an entity X1 at time, t, is the condition of X1 at time, t, expressed as a vector of the entity's attributes.

The underline in the notation ($\underline{SX1}(t)$) is to indicate that the state is a potentially multidimensional quantity.

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Each type of entity will have its own attributes or ways of describing that entity. For example, if the model is to use heterogeneous attrition then the state of a combat unit would depend on at least the following attributes:

(a) Type and number of operational weapon systems

(b) Effective personnel strength

(c) Available ammunition

(d) Available POL

(e) Assigned Mission to include expected arrival time, t_A.

(f) Current location

The attributes of an ammunition supply point might be:

(a) Amounts of various types of ammo on hand

(b) Rates of ammo coming in

(c) Rates of ammo going out

(d) Current location

(e) Units it is suporting

4. Value

Definition: The value of an entity to a particular hierarchical level at time, t, is the relative worth or importance of the entity to that level.

One of the proposals of this thesis is that it is possible to determine the value of an entity at the present time (t_p) and at future times. Let X8 be an entity that is also a level of command. The notation for the value to entity X8 of entity X1 at time, t, given that the states of entity X1 $(\underline{SX1}(t_p))$ and entity X8 $(\underline{SX8}(t_p))$ are known for time, t_p, is $V_{X8}(X1(t)|\underline{SX8}(t_p), \underline{SX1}(t_p))$. This is called notation 1.

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If it is obvious which level is assigning the value, then the notation is shortened to $V(X1(t)|\underline{SX1}(t_p))$; referenced as notation 2.

If there is only one entity under consideration, then notation 2 can be shortened to notation 3a: $V(t|t_p)$. If it is obvious that there is only one time, t_p, under consideration, then notation 2 could be changed to notation 3b: $V(X1(t))$. Finally, if there is only one entity and one time, t_p, notation 2 could be shortened to notation 3c: $V(t)$. See TABLE 1 for a summary of this discussion.

TABLE 1
NOTATION FOR VALUE

Notation	Requirements	Notation Type
$X_{X8}(X1(t)|\underline{SX8}(t_p),\underline{SX1}(t_p))$	None	1
$V(X1(t)|\underline{SX1}(t_p))$	Only one entity is assigning value	2
$V(t|t_p)$	Type 2 Requirement & only one entity is being evaluated	3a
$V(X1(t))$	Type 2 Requirement & only one time, t_p, is being considered	3b
$V(t)$	Type 3a and 3b Requirements	3c

The hierarchical levels referred to in the definition of value are the levels in the chain of command that are represented in ALARM.

5. Power

a. General Definitions

Definition: The power of an entity determined by a par-
ticular hierarchical level is its ability to change or
influence either directly or indirectly the states
of entities that the level will face that belong to the
enemy or that the enemy is planning to use.

It is assumed for all remaining definitions of power

that they are dependent on the level of the hierarchy that

determines the power. However for the sake of brevity the

words "determined by a particular hierarchical level" and

"that the level will face" will not be repeated in each

definition.

Some of the synonyms found in the dictionary for power

are force, strength, and might.[Ref. 8:p. 1089] Anyone fam-

iliar with the terminology used in physics knows that power is

not the same as force. Physicists have very precise definitions

for these terms so that they can use the words in a meaningful

way. Consequently it will assist the combat modeler that has

experience in the field of physics to know the relationship of

the way the word power is used in GVS to the way it is used in

physics. A more complete discussion of this relationship is

found in Appendix A.

One of the assumptions that is made in GVS is that there

are two types of power of an entity: inherent power and de-

rived power. The total power of an entity is the sum of its

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inherent and derived power. An important point that should be noted is that certain entities may have only inherent power, others may have only derived power, while still others may have both.

> Definition: The inherent power of an entity is its ability to directly affect the states of enemy entities or of entities that the enemy is using or planning to use (e.g., a bridge).

Inherent power is the ability to disrupt, delay, or destroy the enemy and is referred to as combat power by the U.S. Army. [Ref. 1:p. 2-4] It includes the lethality, mobility, survivability and efficiency of the entity. Examples of entities that will have inherent power are combat units, combat support units, and to a lesser extent combat service support units. Entities that would probably not have inherent power would be bridges, roads, intelligence gathering units, command and control headquarters, and communication messages.

> Definition: The derived power of an entity is that power it possesses because of its ability to influence the states of other friendly entities or of entities that its forces are planning to use.

Examples of entities that will have derived power are combat and combat support units used as a reserve, combat service support units, and all of the entities listed above as probably not having inherent power. Notice that if an entity does not have inherent power then it must have derived power and vice versa. An entity by definition must have a value assigned to it and value is a function of power. The derived power of an entity eventually results from the ability of that

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entity to change or maintain the inherent power of other enti-
ties. For example, a bridge might contribute directly to the
increase of the inherent power of a combat unit by allowing
that combat unit to move closer to the enemy. In another
situation, that same bridge might contribute to the inherent
power of a combat unit by permitting an ammunition convoy to
get closer to resupplying the combat unit.

b. Specific Definitions

(1) Inherent Power

Definition: The Basic Inherent Power (BIP(X1)) is the inher-
ent power possessed by entity X1 at full strength, when it
is in position to engage its most likely adversary as a
direct result of X1's ability to conduct combat operations.

Full strength means being at full TOE (Table
of Organization and Equipment) with the prescribed load of supplies.
The determination of the position at which the entity achieves
maximum power will be computed in ALARM for each specific
situation.

For each scenario (e.g., NATO, Middle East)
there will be only one BIP for each entity that has a BIP. BIP
is an input provided by the user of the model. It is entirely
possible that the user could apply existing firepower score
methodology to obtain the BIP's for the entities in the model.
Various firepower score approaches were discussed in Chapter 2.

As the battle progresses most entities will not
remain at full strength in all of the areas of equipment, per-
sonnel, and logistics. Therefore adjustments will have to be

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made to the BIP as the situation changes. The following definitions use notation 2 from TABLE 1 (i.e., it is assumed that there is only one level that is evaluating the power of the entities).

Definition: The Adjusted Basic Inherent Power ABIP(SX1(t)) of entity X1 at time, t, is the BIP of X1 adjusted for the specific mission and condition of the entity at time, t.

The entity would have an ABIP amount of power if it was in a position to use that power. The next two definitions deal with the problem of determining the power of an entity that is not yet in a position to accomplish its mission at time, t.

Definition: The Predicted Adjusted Basic Inherent Power PABIP(X1(t) | SX1(t_p)) of entity X1 at time, t_p, is the ABIP that X1 is predicted to have at time, t ($t > t_p$).

The time, t_p, is present time or the time that the prediction is made, and ABIP is assumed known at time, t_p. To actually be a "prediction" t is greater than t_p. For computational purposes if t is less than t_p then PABIP(X1(t) | SX1(t_p)) could be interpreted as an estimate of the power that X1 did have at time, t.

It is proposed that without logistical support, the power of combat units, even when not in contact, decreases monotonically over time. This decay is due to the consumption of supplies, failure of equipment, and noncombat related attrition of personnel. [Ref. 7:p. 8] With the addition of combat losses the power of units without logistical support would decrease even more. The total decrease in power can be characterized, at least to a first approximation, by one of the following functions:

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$$\text{PABIP}(X1(t) \mid \underline{SX1}(t_p)) = \text{ABIP}(\underline{SX1}(t_p)) \times \exp[-L(t-t_p)] \quad \text{(eqn 3.1)}$$

or

$$\text{PABIP}(X1(t) \mid \underline{SX1}(t_p)) = \text{ABIP}(\underline{SX1}(t_p)) \times \exp[-L(t-t_p)^2] \quad \text{(eqn 3.2)}$$

The units of PABIP are STAPOWs. Therefore the units of L, if equation 3.1 is used, are the reciprocal of time. If equation 3.2 is used the units of L are the reciprocal of time squared. For example suppose that a Red Motorized Rifle Regiment (Y1) has a Basic Inherent Power, BIP(Y1)=1200 STAPOWs. Since Y1 is currently short four tanks and does not have a full basic load of fuel, it has 83% of its BIP. Also the present time is $t_p=10$ and the current mission is to attack a Blue tank Battalion. Considering these conditions it is determined that if Y1 was in position to attack with its current assets that the Adjusted Basic Inherent Power of Y1 at time, t_p, would be

$$\text{ABIP}(Y1(t_p) \mid \underline{SY1}(t_p)) = 1000 \text{ STAPOWS} .$$

If the power of Y1 is expected to decay according to the formula in equation 3.1 with the parameter L=0.05 then the graph of PABIP(Y1(t) | $\underline{SY1}(t_p)$) would be that shown in Figure 3.1. If the power of Y1 is expected to decay according to the formula in equation 3.2 with parameter L=0.05 the graph of PABIP(Y1(t) | $\underline{SY1}(t_p)$) would be as shown in Figure 3.2.

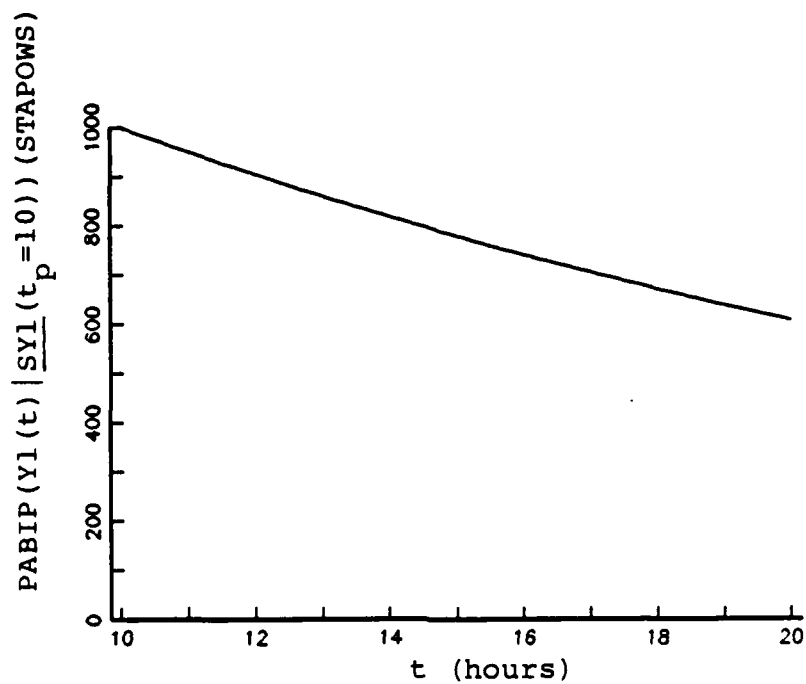Let t_A be the expected time that the entity will be available to conduct its assigned mission or be used by another

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Figure 3.1.   Predicted Adjusted Basic Inherent Power from Equation 3.1.
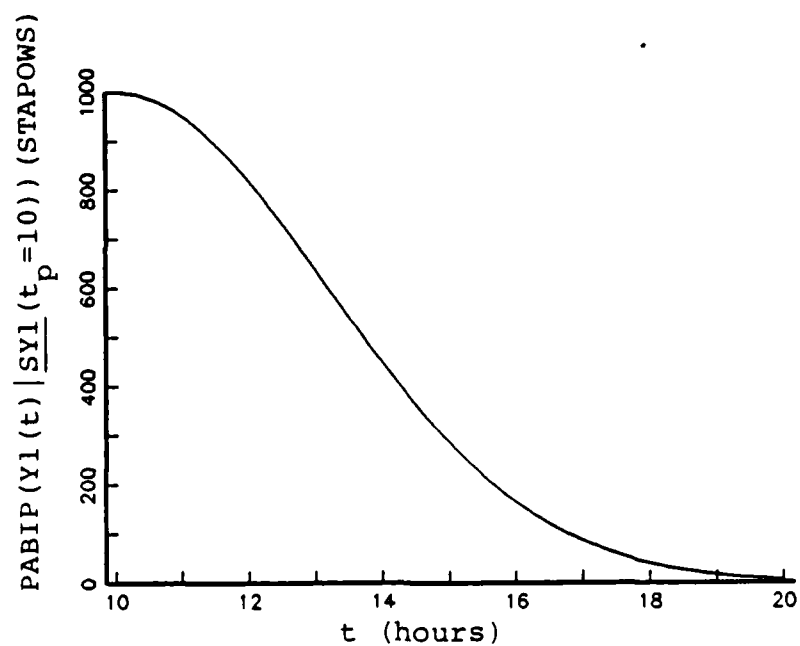
Figure 3.2.   Predicted Adjusted Basic Inherent Power from Equation 3.2.

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entity. This time is computed by extrapolating the unit's current state vector. Substituting $t=t_A$ in equation 3.1 yields

$$PABIP(X1(t_A)|\underline{SX1}(t_p))=ABIP(\underline{SX1}(t_p))\times exp[-L(t_A-t_p)] \quad (eqn \ 3.3)$$

Thus equation 3.3 is used at time t_p to find the power that X1 is expected to have when it arrives at its position to execute its assigned mission. If equation 3.2 is determined to be a better predictor of power then the corresponding equation would be

$$PABIP(X1(t_A)|\underline{SX1}(t_p))=ABIP(\underline{SX1}(t_p))\times exp[-L(t_A-t_p)^2] \quad (eqn \ 3.4)$$

One implication of assuming that equation 3.1 is an accurate model for the decay of power over time is that the rate of decay, L, is constant. L may, in fact, have several components such as attrition, reinforcement, and logistics effects. The assumption that the decay of power can be modeled by the negative exponential is currently thought to be adequate (as a one parameter decay function). Subsequent research may indicate that multiparameter decay functions of the Gamma or Beta class are required. In the actual implementation within ALARM, Lanchester formulations will likely be used to determine the loss rate due to attrition. Once the final form of the Lanchester representation has been determined, the rate of decay can be computed for use in the exponential. A procedure for determining the decay of power due to logistic consumption is given in Appendix C.

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With these definitions it is now possible to deter-
mine the inherent power of entities before, during, and after
the time that they expect to arrive at a position at which
they can accomplish the mission.

Definition: The Situational Inherent Power, $SIP(X1(t)|\underline{SX1}(t_p))$,
of entity X1 is the inherent power that X1 is predicted
at time, t_p, to have at time t.

For times $t < t_A$ it is the PABIP of the entity at
time t_A decremented (or discounted) by an exponential factor
based on the time interval (t_A-t) before the entity will be
in position. For times $t \geq t_A$ it is the Predicted Adjusted
Basic Inherent Power of the entity at time, t.

The assumption is made that power increases exponen-
tially the closer the entity comes to performing its mission.
For equations 3.5 through 3.7 it is assumed that the entity that
is being evaluated is X1 and so notation 3a from TABLE 1 is used.

To calculate the SIP of an entity it is necessary to
know the time it will be ready to perform its mission (t_A)
and the rate at which it is attaining readiness (D) and how
much power it will have when it is ready $(PABIP(X1(t_A)|\underline{SX1}(t_p))$.
To discount the power back to time $t < t_A$:

$$SIP(t|t_p)=PABIP(t_A|t_p)\times\exp[-D(t_A-t)] \qquad (\text{eqn } 3.5)$$

Rearranging the terms in equation 3.5 yields

$$SIP(t|t_p)=PABIP(t_A|t_p)\times\exp[-Dt_A]\times\exp[Dt] \qquad (\text{eqn } 3.6)$$

As with L, in equation 3.1, the units of D are the reciprocal of time. In equation 3.6, $PABIP(t_A | t_p) \times \exp[-Dt_A]$ can be thought of as the power that the entity has at time $t=0$. In essence, the power is being discounted backward for an amount of time, t_A, and then compounded forward for an amount of time, t. Thus,

$$SIP(t | t_p) = PABIP(t_A | t_p) \times \exp[-D(t_A - t)] \quad \text{for} \quad 0 \leq t \leq t_A$$

$$= PABIP(t | t_p) \qquad\qquad\qquad \text{for} \quad t \geq t_A$$

(eqn 3.7)

If it is assumed that PABIP is a constant for $0 \leq t \leq t_A$, then the formula for SIP for $0 \leq t \leq t_A$ is the same as that in the Malthusian model of population growth. [Ref. 10:p. 306] (See Appendix B for a more detailed discussion of the Malthusian model and a variation of it called the limited growth model which uses the "logistics curve".)

Suppose that the example of the Motorized Rifle Regiment Y1 which has $BIP(Y1)=1200$ and $ABIP(Y1(t_p) | \underline{SY1}(t_p=10))=1000$ is continued. Let Y1's time of arrival be $t_A=20$. Suppose that the expected loss of power over time is given by the formula in equation 3.1 with $L=0.05$ (the graph of which is shown in Fig. 3.1). Using equation 3.1, $PABIP(Y1(t_A) | \underline{SY1}(t_p))=606.53066$. If it is assumed that the parameter $D=0.23$ in equation 3.7 then

$$SIP(Y1(t) | \underline{SY1}(t_p)) = 606.53066 \times \exp[-0.23(20-t)] \qquad \text{(eqn 3.8)}$$

The graph of the function in equation 3.8 is shown in Figure 3.3.

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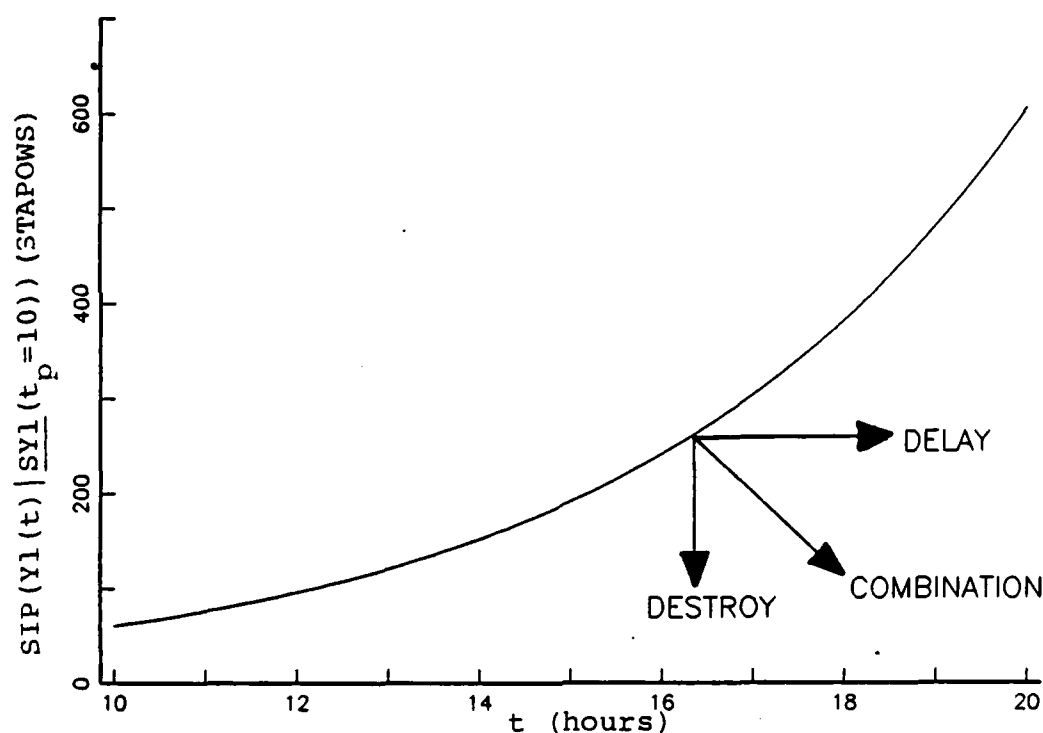
Figure 3.3. Situational Inherent Power from Equation 3.8.

Basically Blue entities can try to do three things to a Red entity: delay it, destroy part or all of it, or a combination of both. These types of actions will affect the power curves of an entity. For example, if Y1 was delayed, the SIP curve in Figure 3.3 would be translated to the right. If some of Y1's assets were destroyed the curve would move down. If Y1 was delayed and some of its assets were destroyed then its power curve would be translated down and to the right.

(2) Derived Power

Definition: The Basic Derived Power, $BDP(X1(t)|\underline{SX1})t_p))$ of entity X1 is the derived power that X1 would have if X1 (at full strength) was in position at time, t, to either increase or maintain the power of another friendly entity.

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The power is computed as if the support could be provided instantaneously when it is required. Note that basic derived power is not unique for each entity since it depends on the mission that the entity is assigned. This definition is not meant to exclude one side from evaluating the supplies in a unit on the other side as a potential source of power. If the Blue side plans to capture and use some of Red's supplies at some time in the future then it would consider these supplies as being on both the Blue and Red sides. Thus the supplies could be treated like a bridge in that either side could use them.

Definition: The Adjusted Basic Derived Power $\overline{ABDP(X1(t)|\underline{SX1}(t_p))}$ of entity X1 is the Basic Derived Power of X1 adjusted for its current capability at time, t_p.

Suppose that X1 is to support entity X2. Suppose the state of X2 without the support is $\underline{SX2B}(t_p)$ and the state of X2 with the support is $\underline{SX2A}(t_p)$. Then the power of entity X1 at time, t, would be

$$ABDP(X1(t)|\underline{SX1}(t_p))=SIP(X2(t)|\underline{SX2A}(t_p))-SIP(X1(t)|\underline{SX2B}(t_p)) \qquad \text{(eqn 3.9)}$$

Definition: The Situational Derived Power, $\overline{SDP(X1(t)|\underline{SX1}(t_p)}$ of entity X1 is the ABDP of X1 decremented by an exponential factor based on the time interval before X1 can perform its mission.

$$SDP(X1(t)|\underline{SX1}(t_p))=\begin{cases} ABDP(X1(t_{AS})|\underline{SX1}(t_p))\exp[-D(t_{AS}-t)] & 0<t<t_{AS} \\ \\ ABDP(X1(t)|\underline{SX1}(t_p)) & t\geq t_{AS} \end{cases} \qquad \text{(eqn 3.10)}$$

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The term t_{AS} is the expected arrival time of the support that X1 is to provide. As an example of calculating derived power, suppose that the Motorized Rifle Regiment (Y1) that was used in the previous example requires fuel. Suppose Y2 is a logistics unit with the mission of resupplying Y1 with fuel at time $t_{AS}=19$. The SIP curve (equation 3.8) shown in Figure 3.3 was calculated assuming that Y1 was not receiving supplies. Using the notation mentioned above, this SIP curve (eqn 3.8) is

$$SIP(Y1(t)|\underline{SY1B}(t_p))=606.53066\times exp[-0.23(20-t)] \quad \text{for} \quad t\leq20 \qquad (eqn \ 3.11)$$

This is equivalent to

$$SIP(Y1(t)|\underline{SY1B}(t_p))=60.810063\times exp[0.23(t-10)] \text{for } t\leq20$$
$$(eqn \ 3.12)$$

Suppose that the parameter, D, that is used to calculate the power of Y1, if it were to receive a continuous supply of fuel until time $t_{AS}=19$, is D=0.27. Thus the power for Y1 receiving a continuous supply of fuel is given in equation 3.13

$$SIP(Y1(t)|\underline{SY1A}(t_p))=60.810063\times exp[0.27(t-10)] \quad \text{for} \quad t\leq19 \qquad (eqn \ 3.13)$$

Substituting equations 3.12 and 3.13 into equation 3.9 yields

$$ABDP(Y2(t)|\underline{SY2}(t_p))=60.810063\times[exp[.27(t-10]-exp[.23(t-10)]] \text{ for } t\leq19$$
$$(eqn \ 3.14)$$

The graph of the function in equation 3.14 is shown in Fig. 3.4. Evaluating the function in equation 3.14 at the point $t_{AS}=19$ yields

$$ABDP(Y2(t_{AS})|SY2(t_p))=60.810063\times[exp[0.27\times9]-exp[0.23\times9]]$$
$$=208.82534 \qquad (eqn \ 3.15)$$
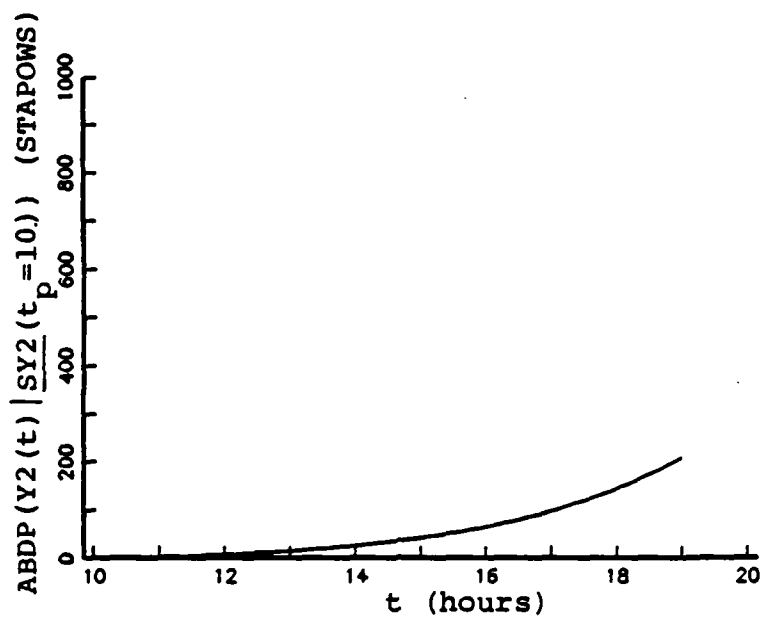
Figure 3.4. Adjusted Basic Derived Power from Equation 3.14.
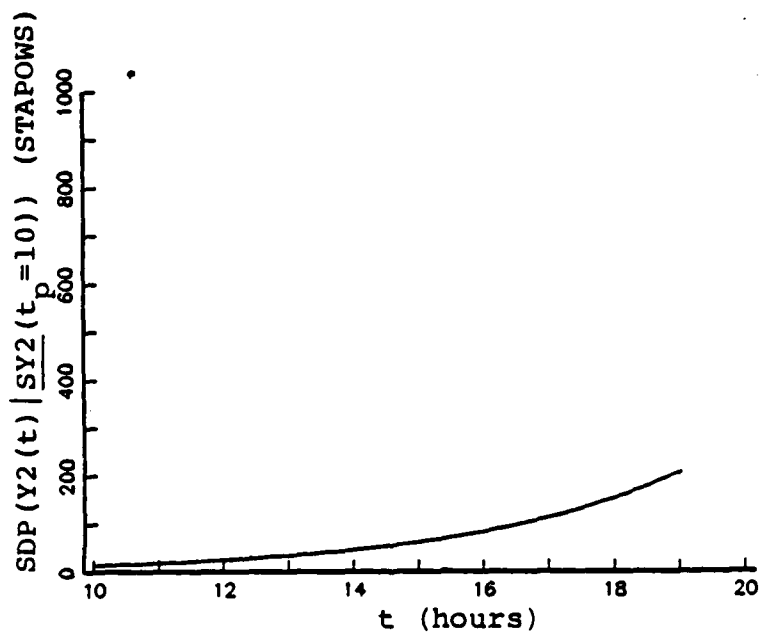
Figure 3.5 Situational Derived Power from Equation 3.16.

Now if the parameter D in equation 3.10 is assumed to be 0.3 substitution into equation 3.10 yields

$$SDP(Y2(t)|\underline{SY2}(t_p))=208.82534\times\exp[-0.3(19-t)]\quad\text{for }t<19$$

$$(\text{eqn } 3.16)$$

$$=0\qquad\qquad\text{for }19<t<20$$

The graph of the function in equation 3.16 is shown in Fig. 3.5.

6. Supply

Definition - The supply of an entity type is a measure
of the quantity of that entity type that is on hand
and available for commitment.

As an entity type becomes more abundant on the battlefield, the value of any one entity of that type decreases. For example, the value to a commander of one tank is higher if he only has 10 tanks than if he has 1000 tanks. Thus the value of an entity is inversely proportional to the supply of that type of entity. The formulation of value is described in the next section.

D. PROCEDURES IN GVS

1. Determining Power

To determine the power of an entity the inherent power is calculated first, followed by the determination of derived power. For example, in the case of logistical support units, first create two sub-entities (A and B) that are interdependent. Sub-entity A provides the inherent (combat) power while sub-entity B provides the support or derived power. If all of the unit's effort is put into support, then the power of sub-entity B would be large and sub-entity A would have no power. If the

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unit's effort is divided more evenly, the ability to support will decrease and the ability to fight would increase. Finally, if no effort was given to sub-entity B then the unit would be able to fight but not to support.

It must be remembered that the power of an entity is calculated based on its assigned mission. For now it is assumed that the model will be able to generate exact missions for each entity. The problem of how these missions will be generated is discussed in Chapter 4.

a. Inherent Power

As stated earlier, it is assumed that the Basic Inherent Power (BIP) of the entities can be determined by the user. If a firepower score approach is used to determine BIP's, then it can also be used to help determine the Adjusted Basic Inherent Power (ABIP) of entities. To do this a heterogeneous rather than homogeneous attrition process will be required so that the powers of entities can be determined from their remaining weapons.

To calculate the Situational Inherent Power it will be necessary to determine the time/decay constant (D) to be used in the exponential. For enemy units it is proposed that the Area of Interest be used to help determine this constant. The Area of Interest for a particular hierarchical level is that area of the battlefield that contains enemy forces that are capable of affecting current and future operations of that level. It is assigned by higher headquarters and is where the

commander focuses his intelligence gathering efforts. [Ref. 1: p. 7-15] This area can be designated in terms of distance or time. For instance, the time given to a division commander may be up to 72 hours. [Ref. 1:p. 6-2] If the time for a division was 36 hours then the division would be looking for targets that were within 36 hours of the FLOT (forward line of troops). A simplistic way of choosing the decay constant would be to assign a negligible amount of power (say 5% of its $\mathrm{PABIP}(X1(t_A)|\underline{SX1}(t_p))$ to an entity that is 36 hours away from the division. Thus the discount factor for a division looking at enemy assets could be determined from the following:

$$0.05 = \exp(-36 \times D) \qquad \text{So that} \quad D = 0.083/\text{hour}. \qquad \text{(eqn 3.17)}$$

Using this approach an enemy unit located 24 hours from the FLOT would have its $\mathrm{SIP} = .14 \times \mathrm{ABIP}$ $(.14 \approx \exp(-0.083 \times 24))$ while a unit only 6 hours away would have an $\mathrm{SIP} = 0.612 \times \mathrm{ABIP}$. [Ref. 7:p. 6] It is important to note that two units could be side by side and yet one be 36 hours away and the other only 4 hours (e.g., a tank company and a dismounted infantry company). Thus while the division's discount factor is .083/hour the time until arrival will be different for different types of entities. Procedures for determining the decay constants for friendly units is a subject for future research.

The Area of Influence is another term that is closely related to and used in conjunction with the Area of Interest. The Area of Influence for a given unit is that portion of the Area of Interest "wherein a commander is capable of acquiring

and fighting enemy units with assets organic to or in support of his command." [Ref. 1:p. 7-15] Thus the area of influence is where the commander fights the current battle and the area of interest is where the commander monitors enemy forces that might influence future operations. [Ref. 1:p. 6-1] Schematics showing the relationship of the Area of Interest and Area of Influence for two levels of command are shown in Figure 4.3.

b. Derived Power

To calculate the derived power of an entity it is necessary to determine how the entity affects the entities that it supports. The following entities could have derived power: logistics units, electronic warfare units, intelligence units, command and control sections, airborne or special reserve units, etc. In fact, depending on the level of detail in the intelligence and communication modules every unit that has a communication capability could have a derived power. That is because these units could provide information that could influence the command and control process which in turn influences when entities will be utilized. Therefore an important component in determining derived power is the power of information. At this stage in the development of GVS it has not been determined how the power of information or the power of command and control will be computed. There is, however, a proposed methodology for determining the derived power of logistical units (see Appendix C).

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2. Determining Value

The power of an entity as perceived by a given hierarchical level is considered the short term importance of that entity. Suppose that it is known that the upcoming battle is the last battle of the war. Whoever wins the battle wins the war. The value of any given entity is solely determined by its contribution to winning that battle. Thus the value of an entity would be directly proportional to its power in such a situation. Now suppose the upcoming battle is the first battle of the war and there are no shortages of any of the entity types. (i.e., the commanders are in the unlikely but envious position of having the things they want in the proper proportions.) Here again value would be directly proportional to power.

For any other battle the availability of different types of entities is likely to vary across the battlefield. Thus it is possible that the Corps could have an adequate combination of entity types to face a specific enemy force even though one division is short tank companies and another division is short ammunition. Thus, a resource that is abundant at one level of command may be scarce at another level. Because there is more than one battle to be fought, it may be important not to use (and possibly lose) all the scarce assets in the current battle. The long term importance of entities reflects not only the power but also the supply of these entities. Thus, value is related to long term importance.

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There are two primary purposes for considering the value of entities:

(a) To determine which targets should be prosecuted by a given asset;

(b) To determine which asset should prosecute a given target.

The methodology proposed for computing value does not directly address how these values will be used to accomplish these purposes. Rather it presents a comprehensive method for determining the value of either friendly, enemy, or neutral entities from the perspective of either side.

Once the power of an entity is determined, there are two steps involved in calculating the value of an entity. The first step is the specification of the value of each asset type in the unit as a function of its current ABIP by the use of utility curves. This gives the long term usefulness of the entity or Usefulness Value (UV). These curves are based on the assumption that each asset in the unit will remain in the same proportion in the unit throughout the battle. The second step scales the usefulness value obtained in the first step to account for the scarcity of the asset and obtain the value (V) of the entity. The scaling factor relates the desired proportion of entity types to the existing mix of entity types. Thus the first step determines the long term usefulness of the entity and the second step determines the supply or availability of the entity.

Examples of the types of utility curves that have been considered are shown in Figures 3.6 and 3.7.

Using the language of utility theory, Figure 3.6 shows a risk preferring individual, whereas Figure 3.7 shows a risk averse decision maker. A risk indifferent decision maker would have a straight line from the point (0,0) to the p int (1000,1000). A family of exponential utility curves that could be used to depict this type of behavior is given in equation 3.18.

$$UV(x) = BIP \times \frac{1-\exp[G \times \frac{x}{BIP}]}{1-\exp[G]} \qquad \text{(eqn 3.18)}$$

The x in equation 3.18 is actually $SIP(X1(t)|\underline{SX1}(t_p))$. The curve for BIP=1000 and G=3 is shown in Figure 3.6. For BIP = 1000 and G=-3 the curve is shown in Figure 3.7. For G=0 the curve would be the indifference curve or straight line.

The proposed methodology for dealing with the availability aspect of value is to have the user provide the "desired" proportions (DP) of assets to have in facing a specified enemy force for a given mission. For each entity type, the user would specify the desired ratio of the power of that type of entity to the power of the entire force. An example is provided below for two entity types. Since all calculations are made for $t_p=0$, notation type 3b from Table 1 will be used. Thus $V(X1(t)|\underline{SX1}(t_p))$ is shortened to $V(X1(t))$. Let DP_j = Desired Proportion of type j assets.
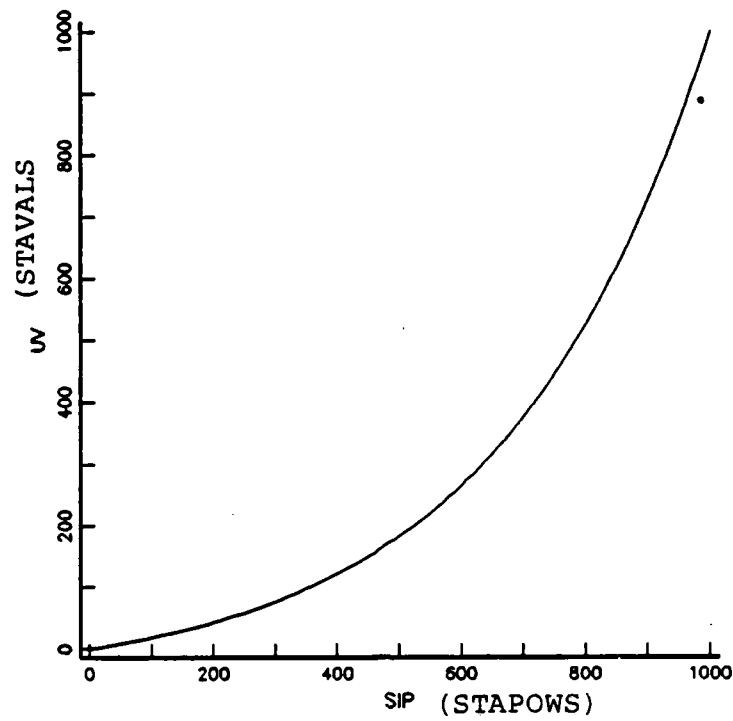
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Figure 3.6. Usefulness Value for G=+3 from Equation 3.18.
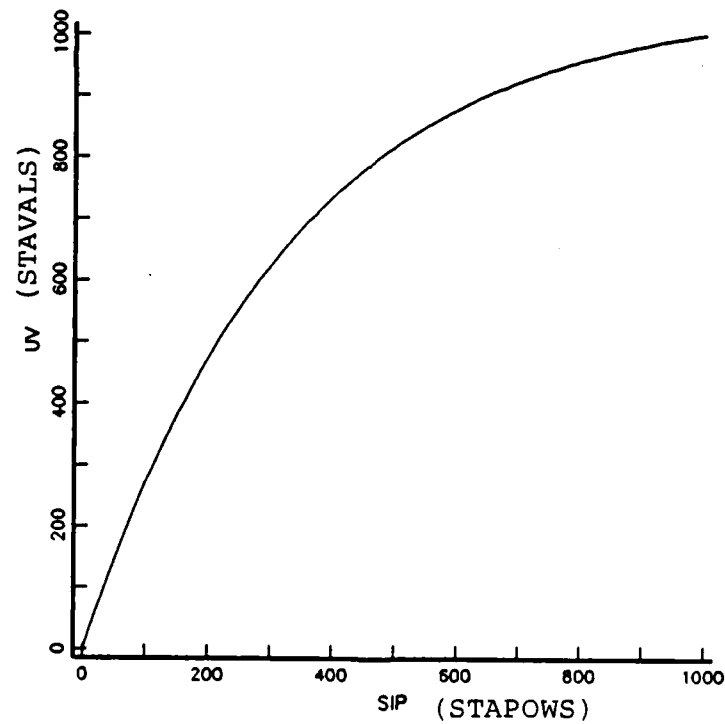
Figure 3.7. Usefulness Value for G=-3 from Equation 3.18.

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$$DP_1 = \frac{\Sigma \; BIP(type \; 1)}{\Sigma \; BIP(All \; types)} \quad and \quad DP_2 = \frac{\Sigma \; BIP(type \; 2)}{\Sigma \; BIP(All \; types)} \quad (eqn \; 3.19)$$

Now suppose entities X_1, X_2, X_3 are of type 1 and X_4, X_5 are type 2

$$DP_1 = \frac{\sum_{i=1}^{3} BIP(X_i)}{\sum_{i=1}^{5} BIP(X_i)} \quad and \quad DP_2 = \frac{\sum_{i=4}^{5} BIP(X_i)}{\sum_{i=1}^{5} BIP(X_i)} \quad (eqn \; 3.20$$

Obviously $\sum_{all_i} DP_i = 1$ is a requirement that must be met.

Let CP_j = Current Proportion of type j assets on hand.

$$Thus \quad CP_1 = \frac{\sum_{i=1}^{3} ABIP(Xi)}{\sum_{i=1}^{5} ABIP(Xi)} \quad and \quad CP_2 = \frac{\sum_{i=4}^{5} ABIP(Xi)}{\sum_{i=1}^{5} ABIP(Xi)} \quad (eqn \; 3.21)$$

Once the desired and current proportions are known the following formula is applied to determine the value of entity X of type a.

$$V(X(t)) = \frac{DP_a}{CP_a} \times UV(X(t)) \quad (eqn \; 3.22)$$

Continuing the example suppose

$$DP_1 = 0.3, \quad CP_1 = 0.1, \quad DP_2 = 0.7, \quad CP_2 = 0.9,$$

$$UV(X_1(t)) = 100, \quad and \quad UV(X_4(t)) = 500.$$

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Then $V(X1(t)) = \frac{0.3}{0.1} \times 100 = 300$ and $V(X4(t) = \frac{0.7}{0.9} \times 500 = 389.$

This method causes the value of a specific entity to increase as that type of asset becomes increasingly scarce, as would be the case where $CP_j < DP_j$.

The following example is provided to illustrate how the value of an entity is calculated. Suppose the conditions are those given in TABLE 2 for Case 1 and Case 2.

TABLE 2

DATA FOR AN EXAMPLE OF VALUE CALCULATION

	Case 1	Case 2
BIP(Y1)	1300	1300
ABIP($\underline{SY1}(t_p)$)	1200	300
L	-0.0182321	0.1203972
D	0.0748933	0.0748933
t_0	0	0
t_p	30	30
t_A	40	40

Equation 3.1 is used to compute $PABIP(Y1(t)|\underline{SY1}(t_p))$. The curve for Case 1 is shown in Figure 3.8 and for Case 2 in Figure 3.9. In each case the predicted power at t_A is 1000. Case 1 could be interpreted as the unit being close to full strength initially but is using more supplies then it is receiving. Case 2 could be interpreted as the unit being very low on supplies at t_p but is receiving more supplies than it is using.

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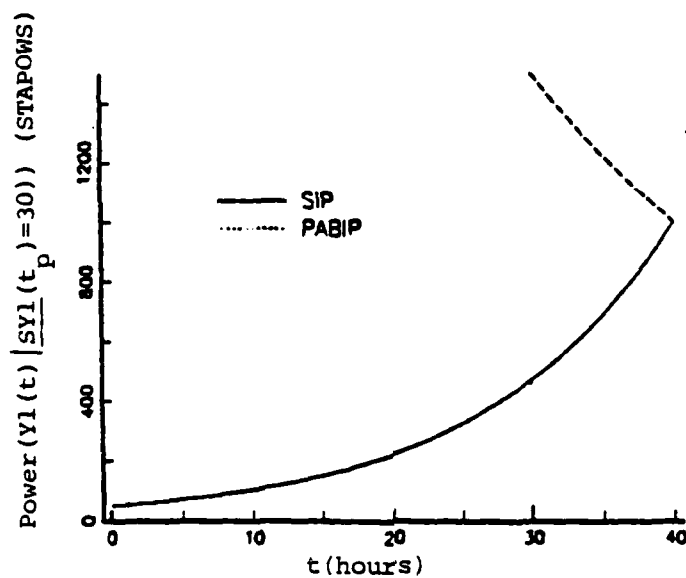
Figure 3.8. Power for Case 1.
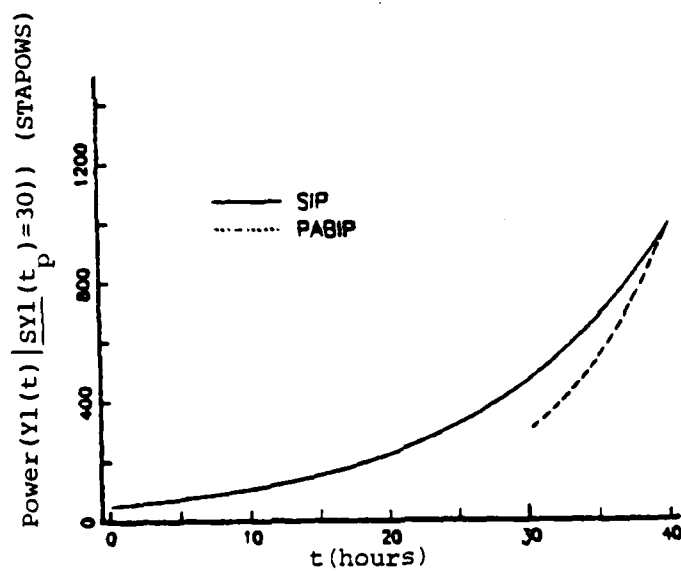
Figure 3.9. Power for Case 2.

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Equation 3.5 is used to determine the SIP curves.

Substitution into equation 3.3 yields the same formula for

both cases.

$$SIP(Y1(t)|\underline{SY1}(t_p))=1000\times\exp[-0.074893\times(40-t)] \text{ for } t<40.$$

(eqn 3.23)

The graph of the SIP curve is shown in both Figure 3.8 and

Figure 3.9. Once the SIP curve has been determined the next

step is to obtain the Usefulness Value curve. Equation 3.18 is

used to calculate the Usefulness Value.

Three Usefulness Value curves are shown in Figure 3.10,

those with: G= -3, G=0 and G=3 . The curve for G=0 is the

same as the SIP curve. Any particular point on the curve can

be checked by using the graphs found in Figures 3.6 and 3.7.
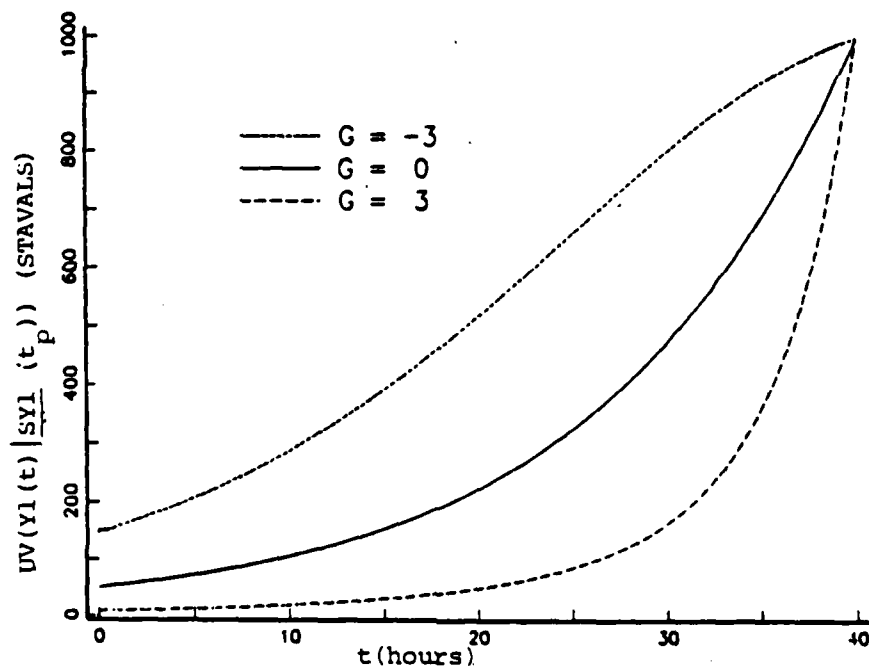
Figure 3.10. Usefulness Value for Case 1 and Case 2.

The last step is to compute the value curves using equation 3.22. The graphs of the value curves for $\frac{DP}{CP} = \frac{1}{2}$ are shown in Figure 3.11.
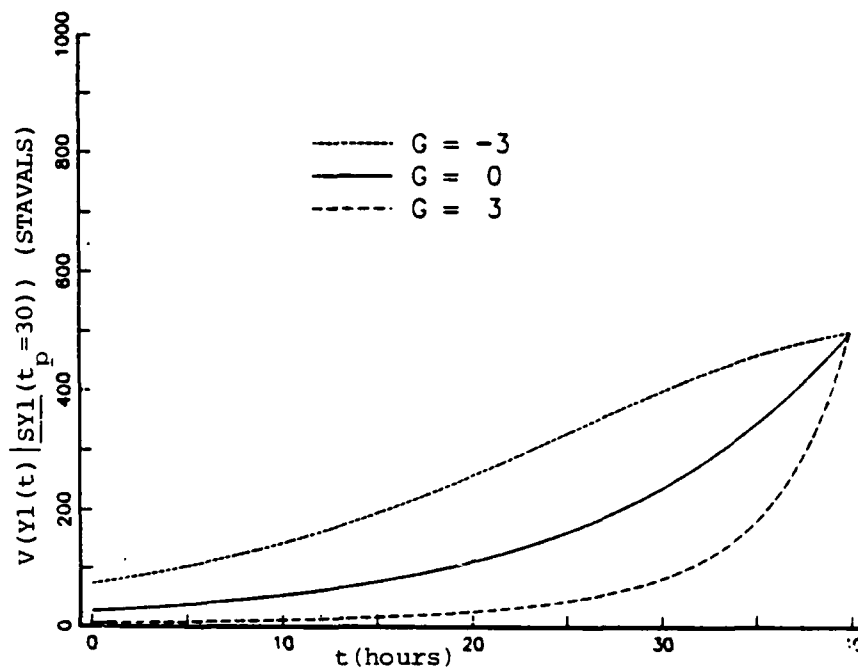
Figure 3.11. Value for Case 1 and Case 2.

3. Average versus Instantaneous Power and Value

To this point the power of an entity has been described as a function only of the state of the entity at a point in time, t: instantaneous power. For many decisions it may be important to know the average power of an entity over an interval of time rather than at a particular instant in time. In this section it is assumed that the entity that is being evaluated is always X1, thus notation 3c of Table 1 is used in this section. The following definition is given for the average

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power $P_A(t_1,t_2)$ that X1 is predicted, at time, t_p, to have over the interval $(t_1 \leq t_A \leq t_2)$.

$$P_A(t_1,t_2) = \frac{1}{t_2-t_1} \int_{t_1}^{t_2} \text{Power}(t)\,dt \qquad (\text{eqn } 3.24)$$

[Ref. 10:p. 261].

Thus average PABIP would be given by

$$\text{PABIP}_A(t_1,t_2) = \frac{1}{t_2-t_1} \int_{t_1}^{t_2} \text{PABIP}(t)\,dt \qquad (\text{eqn } 3.25)$$

If PABIP(t) = PABIP is a constant then

$$\text{PABIP}_A(t_1,t_2) = \frac{1}{t_2-t_1} \int_{t_1}^{t_2} \text{PABIP}\,dt = \frac{\text{PABIP}(t_2-t_1)}{t_2-t_1} = \text{ABIP} \qquad (\text{eqn } 3.26)$$

The average SIP would be given by

$$\text{SIP}_A(t_1,t_2) = \frac{1}{t_2-t_1} \left[\int_{t_1}^{t_A} \text{PABIP}(t) \times \exp[-D(t_A-t)]\,dt + \int_{t_A}^{t_2} \text{PABIP}(t)\,dt \right] \qquad (\text{eqn. } 3.27)$$

Equations similar to 3.25 and 3.27 could be written for average adjusted derived power, situational derived power, and value. If PABIP(t)=PABIP is a constant then substituting into equation 3.27 yields

$$\text{SIP}_A(t_1,t_2) = \begin{cases} \dfrac{1}{t_2-t_1}\left[\int_{t_1}^{t_A}\text{PABIP}\times\exp[-D(t_A-t)]\,dt + \int_{t_A}^{t_2}\text{PABIP}\,dt\right] & (\text{eqn } 3.28) \\[2em] \dfrac{\text{PABIP}}{t_2-t_1}\left[\exp[-D\times t_A]\times\int_{t_1}^{t_A}\exp[Dt]\,dt + \int_{t_A}^{t_2}dt\right] & (\text{eqn } 3.29) \end{cases}$$

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Performing the integration in equation 3.29 yields

$$SIP_A(t_1, t_2) = \frac{PABIP}{t_2 - t_1} \times \left[\frac{exp[-D \times t_A]}{D} \times \left(exp[D \times t_A] - exp[D \times t_1] \right) + (t_2 - t_A) \right] \quad (eqn\ 3.30)$$

Simplifying equation 3.30 yields

$$SIP_A(t_1, t_2) = \frac{PABIP}{t_2 - t_1} \times \left[\frac{1 - exp[-D(t_A - t_1)]}{D} + (t_2 - t_A) \right] \quad (eqn\ 3.31)$$

It can be easily seen by examining a Taylor series expansion of $exp[-D(t_A - t_1)]$ that

$$exp[-D(t_A - t_1)] \geq 1 - D(t_A - t_1) \quad (eqn\ 3.32)$$

Thus by multiplying equation 3.32 by -1 the following occurs:

$$-exp[-D(t_A - t_1)] \leq -(1 - D(t_A - t_1)) \quad (eqn\ 3.33)$$

Adding 1 to both sides of equation 3.33 gives

$$1 - exp[-D(t_A - t_1)] \leq D(t_A - t_1) \quad (eqn\ 3.34)$$

Since it is assumed in the definition of SIP that D is positive the following result occurs when both sides of equation 3.34 are divided by D.

$$\frac{1 - exp[-D(t_A - t_1)]}{D} \leq (t_A - t_1) \quad (eqn\ 3.35)$$

Performing various mathematical manipulations to both sides of the inequality yields

$$\frac{PABIP}{t_2 - t_1} \left[\frac{1 - exp[-D(t_A - t_1)]}{D} + (t_2 - t_A) \right] \leq \frac{PABIP}{t_2 - t_1} \left[(t_A - t_1) + (t_2 - t_A) \right] \quad (eqn\ 3.36)$$

From equation 3.31 the left side of the inequality is recognized as $SIP_A(t_1,t_2)$ thus

$$SIP_A(t_1,t_2) \leq \frac{PABIP}{t_2-t_1}(t_2-t_1) = PABIP \qquad \text{(eqn 3.37)}$$

When considering enemy units the parameter, D, is determined using the area of influence of a level of command. As the area of interest gets larger the parameter D gets closer to 0. This can be seen in the example given earlier where $.05=\exp^{-36\times D}$ and 36 was the number of hours in the area of interest. As the area of interest increases to infinity, the parameter, D, approaches 0 and as the area of interest shrinks to zero the parameter, D, approaches infinity.

In the case when PABIP is a constant and the area of interest becomes very large (and so D approaches 0) then $SIP(t_1,t_2)$ approaches PABIP. This can be shown by using the Taylor series expansion of $\exp[-D(t_A-t_1)]$.

$$\exp[-D(t_A-t_1)]=1-D(t_A-t_1)+\frac{(D(t_A-t_1))^2}{2!}-\frac{(D(t_A-t_1))^3}{3!}+\dots$$
$$\text{(eqn 3.38)}$$

From equation 3.38 it can be seen that

$$\frac{1-\exp[-D(t_A-t_1)]}{D}=(t_A-t_1)-\frac{D(t_A-t_1)^2}{2!}+\frac{D^2(t_A-t_1)^3}{3!}-\dots$$
$$\text{(eqn 3.39)}$$

Substituting equation 3.39 into equation 3.31 yields

$$SIP_A(t_1,t_2) = \frac{PABIP}{t_2-t_1} \times \{[(t_A-t_1) - \frac{D(t_A-t_1)^2}{2!} + \frac{D^2(t_A-t_1)^3}{3!} - \ldots] + (t_2-t_A)\} \quad \text{(eqn 3.40)}$$

It is then obvious that

$$\lim_{D\to 0} SIP_A(t_1,t_2) = \frac{PABIP}{t_2-t_1} \times \{[(t_a-t_1) - 0 + 0 - \ldots] + (t_2-t_A)\}$$

$$\text{(eqn 3.41)}$$

$$= \frac{PABIP}{t_2-t_1} \times (t_2-t_1+t_2-t_A)$$

$$= PABIP$$

Also if PABIP is a constant and if the area of interest becomes very small then D will approach infinity.

Again from equation (3.31)

$$\lim_{D\to\infty} SIP_A(t_1,t_2) = \lim_{D\to\infty} \frac{PABIP}{t_2-t_1} \left[\frac{1-\exp[-D(t_A-t_1)]}{D} + t_2-t_A \right]$$

$$\text{(eqn 3.42)}$$

$$= \frac{PABIP}{t_2-t_1} \left[0 + t_2-t_A \right] = PABIP \times \frac{t_2-t_A}{t_2-t_1} \quad .$$

However, if the area of interest is very small then t_1 will be close to t_A and so $SIP_A(t_1,t_2) \approx ABIP$.

These definitions and procedures constitute GVS as it has been developed so far. While there is considerable work still to be done to implement GVS within ALARM, the framework for doing this is provided in this chapter. The next subject to be addressed is the use of GVS in decision making algorithms.

IV. USING GVS IN DEVELOPING DECISION ALGORITHMS

A. CURRENT VERSUS FUTURE STATE DECISION MAKING

The method used by many existing combat models to make decisions is "current state decision making." This type of decision making is basically deciding at time, t, what should be done at time, t+x, based on the situation at the current time, t. While some of the decisions in ALARM may use this approach, an alternate approach called "future state decision making" has been developed for use in ALARM. Basically "future state decision making" is deciding at time, t, what should be done at time, t+x, based on what the situation is expected to be at time, t+x.

This approach requires algorithms to predict future states from the situation at time, t, and the forecasted rate of change of the variables over (t,t+x). The GVS provides the framework for representing forecasted future states of entities in continuous time. Various combinations of exponential functions are used to represent these forecasts. In general, the length of these forecasts (in time) will be at least for the unit's area of influence and probably at most for the unit's area of interest (both measured in units of time).

In addition to providing these forecasts of future states of entities over time, the GVS must also be capable of determining when a decision should (or must) be made.

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For example, suppose that a Brigade has forecasted power and value curves for both the Brigade and potential threatening enemy units for the next twelve hours. The various predicted curves of value and power are compared to determine if any filters (e.g., amount of power facing one battalion is greater than 5 to 1) have been violated. Once all violated filters have been identified, each is examined and the possible corrective actions that could be taken are determined from the functional modules. Suppose, at time t, only one filter is expected to be violated at time, $s=t+x$, and there are three alternatives (A, B, and C) that could be employed to correct the problem. Let m and M be the minimum and maximum, respectively, of the warning times (time required to plan, prepare, and initiate execution of the alternatives) for A, B, and C. If all three options are to be considered, the decision must be made by time $s-M$. In the interval $(s-M, s-m)$ the number of options is reduced, assuming no change in the situation, and time, $s-m$, is the latest that a decision can be made.

It is possible that in the interval $(t, s-M)$, the predicted situation at time, s, is changed so that the filter is no longer violated. Also, additional options could become available in that interval. In these cases, the time frame and/or options for the decision are modified. Note that this modification would not be possible using "current state decision making".

If it is assumed that the "best" time to make a decision on how to deal with a specific threshold violation is between t and s-M then how is this "best" time to be determined? The standard Army response is that each level of command could take up to 1/3 of the available time for its own planning/decision making and allocate at least 2/3 of the time to its subordinates. While this is an easy rule to remember, it doesn't necessarily determine the "best" time (i.e., is 1/4 better than 1/3). ALARM will be used to conduct sensitivity analyses for planning. It is likely that the "best" fraction of time depends on the type of mission (i.e., attack, defend, withdraw), the total number of violated filters at a given level, and on the confidence that the decision maker has in the available intelligence at time, t.

Before proceeding with the details of how GVS can be used within decision making algorithms, it is essential that the decision problem in any specific situation be stated precisely. For instance, one decision problem might be to maximize enemy power destroyed subject to the friendly value destroyed being smaller than a specified amount. Another problem might be expressed as minimize (friendly value destroyed-enemy value destroyed) subject to destroying a specified bridge by a certain time. Alternatively, another situation may choose the asset/target combination based on $\text{MAX}\left(\dfrac{\text{ENEMY POWER DESTROYED}}{\text{FRIENDLY VALUE USED}}\right)$.

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Friendly value used refers to the actual value of the entity committed to the mission. This last alternative will be used in the example presented in section C.

The following are methodologies which have been conceptually developed for "future state decision making".

    (1)   Value and power curves of entities as a function of time

    (2)   The rate of change over time of the value and power curves

    (3)   Average value and average power of entities over intervals of time.

The determination as to which method will be used in each decision algorithm will be made by the individuals that develop the algorithm. An example showing how these tools will be used is given in section C.

B. DECISION MAKING IN ALARM

To understand how decisions will be made in ALARM it is essential to understand the planning and execution modules.

> The planning module includes the decision algorithms and hence contains both the functions of planning and deciding on a specific course of action. The planning module actually consists of several submodules. In particular there is a planning submodule for each hierarchical level of the maneuver task force organization (i.e., company, battalion, brigade, division, and corps) to represent those planning activities and decisions accomplished by the unit commander and his immediate staff. In addition, there are planning submodules for each of the supporting functions (i.e., FA, ADA, LOG, Maintenance/ recovery, Air, etc.) which formulate plans and make decisions related to that supporting function. [Ref. 3:p. 11]
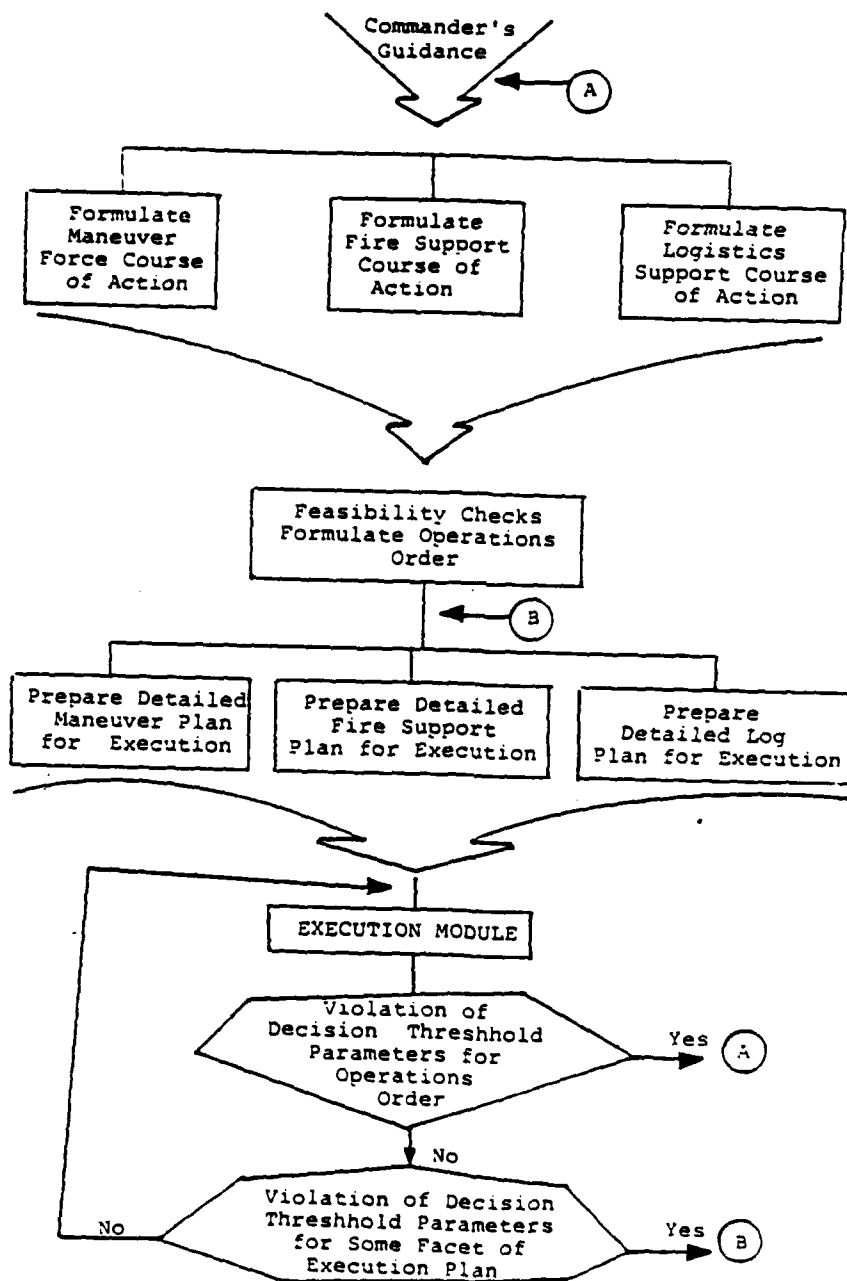
Figure 4.1

Planning Submodule Flow for a Blue Organizational Unit

The stages of the planning submodule for one level in the Blue hierarchy are shown in Figure 4.1. [Ref. 3:p. 12] At least initially, the inputs to ALARM will be in the form of a detailed operations order for a specific mission (i.e., at point B in Figure 4.1). As progress is made in this area, the effort will be extended to the development of algorithms that will generate courses of action directly from the commander's guidance (i.e., at point A in Figure 4.1). [Ref. 3:p. 13] A comparable but more complex planning cycle for a Red unit is discussed on page 16 of reference 3.

A decision support system which uses the planning module to determine the value of entities as targets has been conceptualized and is shown in Figure 4.2. This system considers the problem of deciding on interdiction targets as opposed to targets in the "close-in" battle.

The process of imputing values to numerous targets can be decomposed into a series of steps as follows:

(1) The Intel models will provide the input to the planning model which describes the perceived attributes of the potential targets. Among these attributes are the location, strength, disposition and intention of enemy units. The data base must also be updated to reflect the current combat potential of friendly forces.

(2) The planning model must be invoked to generate the tactical plan to be used for the upcoming operation. As previously described, a hierarchy of network models exist to accomplish such an operation. Without using the information collected on the potential targets, the network drivers can be executed, providing the expected time to complete the mission. Since the planning models are deterministic and hence fast to execute, the driver programs can be repeated inputing one of the potential targets at each iteration.
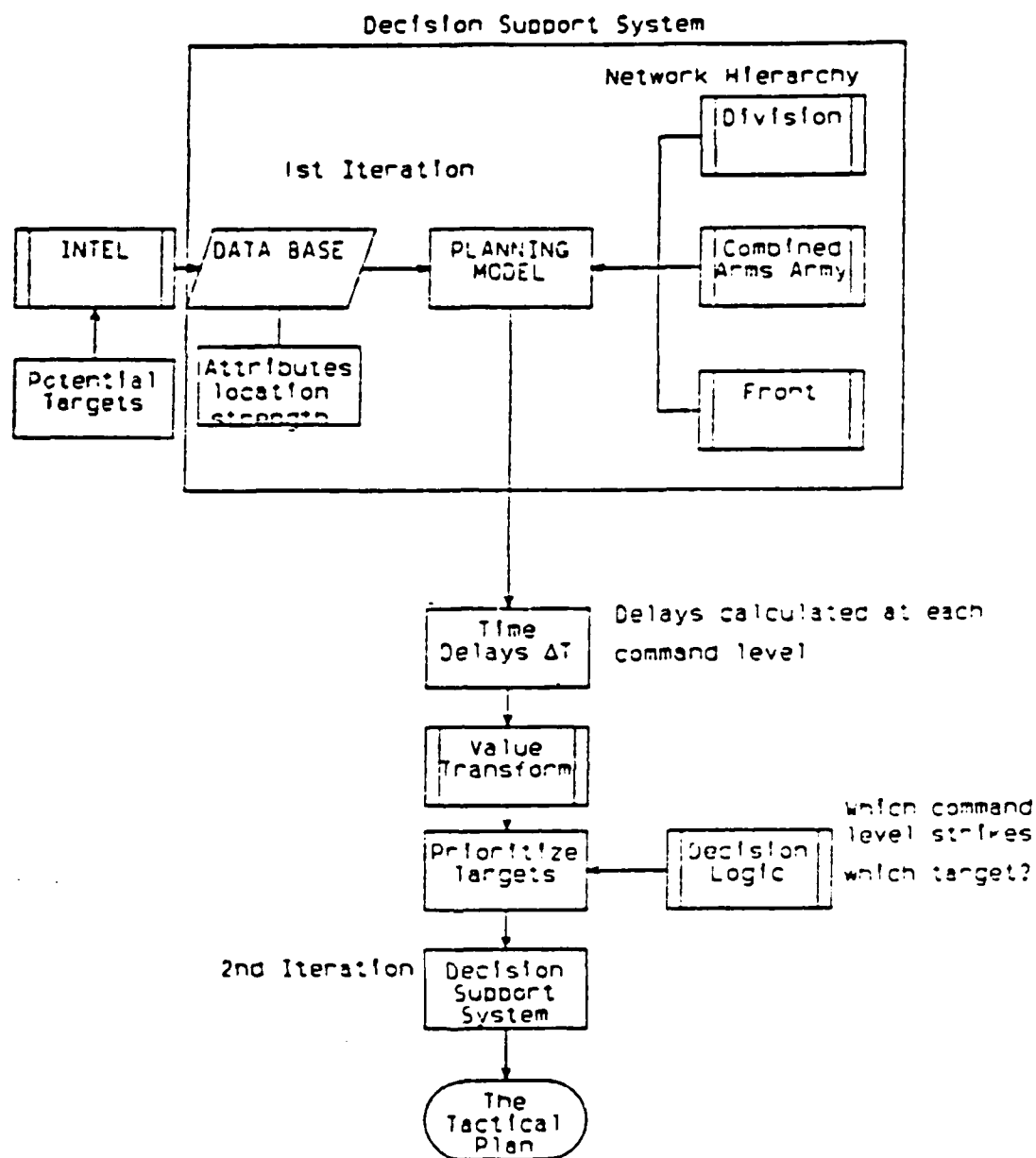
Figure 4.2

Use of the Planning Module to Impute Values

(3) Each iteration of the model at each command level provides a quantifiable change in the expected time to complete the mission. These times encompass attrition losses as well since Lanchester equations are used to assess the results of combat.

(4) The time estimates must be transformed by some process to take into account spheres of influence for each command level and the probability that a strike against the target can be successful.

(5) Use the imputed values to prioritize the potential targets and generate the fire support plan.

(6) Use the fire support plan in the driver programs as the final iteration. This insures that the feasibility criteria are met and that the operations plan at each level reflects the fire support plan.

The advantage of a network hierarchy becomes apparent in the attempt to determine the relative value of targets to the different command levels. A tank battalion located in a Red Division rear area will have a different value to a Blue Brigade Commander than to a Blue Division Commander. This would be especially true if the perceived intention of the tank battalion is that it will be committed as a reserve force against the brigade. The hierarchy of networks approach to decision-making makes it possible to quantify the potential threat to a particular unit by using the planning network for that command level. [Ref. 3:pp. 26-28]

C. EXAMPLE OF DECISION MAKING WITH GVS

The following example is used to illustrate the calculation and use of the value and power of entities. This example is not meant to be all-encompasing but is used to point out particular features and approaches for using the Generalized Value System in decision making algorithms.

1. Scenario

A Blue Armored Brigade is defending a specified area against an approaching Red Motorized Rifle Division. The Brigade mission is to prevent the Red Division from advancing

past the current location of the Brigade's rear boundary in the next 8 hours. The Blue Brigade will be successful if it accomplishes the mission and loses no more than 50% of its 3 subordinate Battalion's power, 75% of its field artillery power, and 30% of its attack helicopter power. The entities that are included in this example along with the percentage of Basic Inherent Power that they currently have on hand are given in TABLE 3.

TABLE 3

ENTITIES IN FUTURE STATE DECISION MAKING EXAMPLE

Entity	Entity Type	BIP	On Hand Power (% of BIP)
X1	Blue Tank Battalion	1000	100
X2	Blue Tank Battalion	1000	100
X3	Blue Tank Battalion	1000	100
X4	Blue Helicopter Company	800	100
X5	Blue Field Artillery Btry	600	100
X6	Blue Tank Brigade	4800	100
Y1	Red Motorized Rifle Reg.	3000	50
Y2	Red Motorized Rifle Reg.	3000	60
Y3	Red Motorized Rifle Reg.	3000	100
Y4	Red Tank Regiment	3600	100
Y5	Red Ammunition Convoy	100	100
Y6	Red Motorized Rifle Div.	14000	80

Notice that the power of the Brigade is not just the sum of its parts nor is the Division power just the sum of the powers of its subordinate units. This concept was discussed in Chapter 3. A pictorial representation of the situation is given in Figure 4.3 in relation to the areas of interest and

influence for the Blue forces. For any given scenario in the real world the boundaries of these areas are likely to form irregular shapes as in part (a) of Figure 4.3. However, to simplify the presentation of the example the representation of the battlefield will be as shown in part (b) of Figure 4.3.

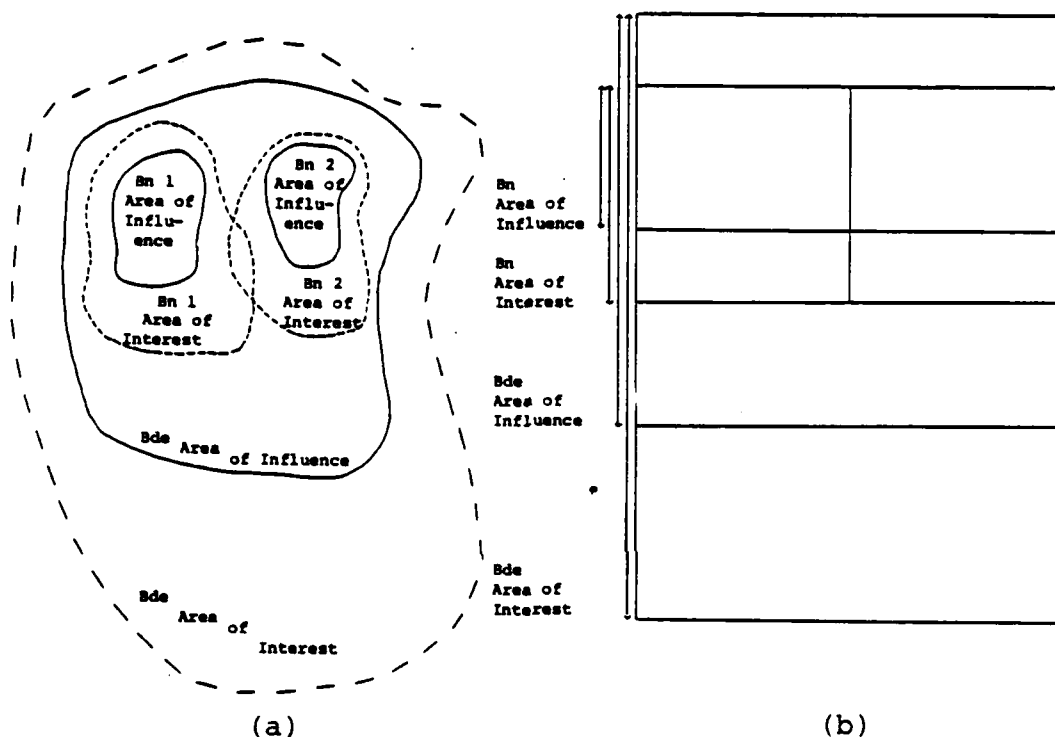(a)   (b)

Figure 4.3
Areas of Influence and Interest

For the purposes of this example the interactions of the Blue Brigade with Brigades on either side (if they exist) will not be considered.

2. Initial Situation

The position of the forces at time $t_p = 0$ (where t_p is the present time in hours) is shown in Figure 4.4. Regiments 1 and 2 have just finished fighting the Blue Division's covering force. Blue intelligence reports indicate that Y1 lost very little personnel and equipment but has expended most of its ammunition. Also intelligence indicates that Y2 has lost about 30% of its vehicles, but if Y2 cross levels its supplies it will not need additional ammunition or fuel in the immediate future. Thus the Blue Brigade expects that Y1 and Y2 will not continue the attack until they are resupplied and/or reorganized. However, Y3 and Y4 are expected to pass Y1 and Y2 in order to maintain the momentum of the Division attack. The most likely avenues of approach of Y3 and Y4 (and their expected locations at times $t = 1, 2, 3$ and 4) are shown in Figure 4.4. Thus the expected time of arrival (t_A) of Y3 is at $t = 4$ and of Y4 is at $t = 3$. (The method of determining the avenues of approach is being developed in a thesis at the Naval Postgraduate School by Captain Doug Fletcher. His thesis will address the issue of initial location of the Battalions when a Brigade meets an opposing force). For this example it is assumed that the avenue of approach methodology would put X1 and X2 in the positions indicated in Figure 4.4 and that the other assets would initially be uncommitted.

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The time that is used in the example is considered simulation time where t=1 is one hour from t=0. It is assumed

Figure 4.4

Position of Forces at $t_p = 0$.
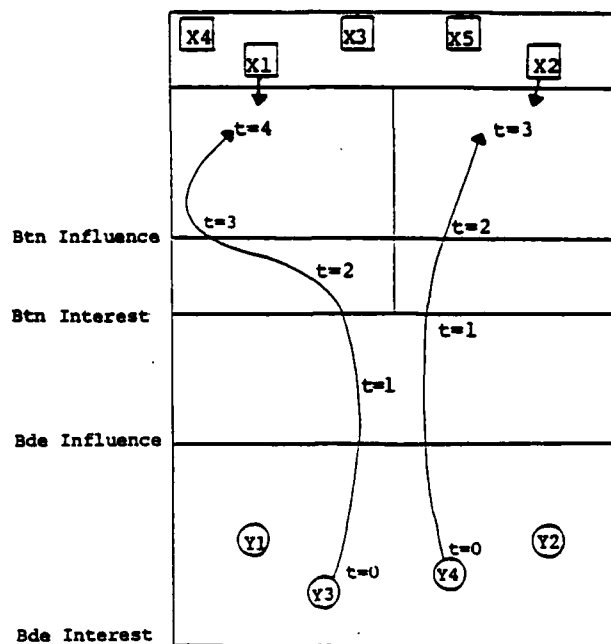
that when an entity is moving, its rate of advance toward its objective is constant so that simulation time can be used in the formulas for determining power and value.

3. Deriving SIP Curves

Suppose that the Brigade attempts to predict the situation up to 6 hours from the current time. For the sake of brevity the derivation of only one SIP curve will be shown in detail.

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The Basic Inherent Power of Y4 was given as 3600. Suppose the Adjusted Basic Inherent Power is determined to be 3800. (Y4 has 100% of its personnel, equipment and supplies and Y4 is expected to be slightly better against its predicted opponent than against its "most likely" opponent on which BIP is based). Suppose the rate of power loss for Y4 is 3% per hour of its current power when it is not in contact and is 10% per hour when it is in contact. All of the equations from 4.1 through 4.10 are concerned with evaluating Y4. Thus the notation 3(a) from Table 1 will be used for all of these equations and so $PABIP(Y4(t) \mid SY4(t_p))$ is shortened to $PABIP(t \mid t_p)$.

The formula (from equation 3.1) for the Predicted Adjusted Basic Inherent Power of Y4 at time $t = t_p + 1$ is:

$$PABIP(t_p+1 \mid t_p) = ABIP(t_p) \times exp[-L(t_p+1-t_p)] \qquad \text{(eqn 4.1)}$$

Since the power that Y4 loses per hour is 3% of its current power when it is not in contact the amount of power that it retains per hour when not in contact is 97% of its current power. Therefore

$$PABIP(t_p+1 \mid t_p) = 0.97 \times ABIP(t_p) \qquad \text{(eqn 4.2)}$$

Substituting from equation 4.2 into equation 4.1 yields

$$0.97 \times ABIP(t_p) = ABIP(t_p) \times exp[-L] \qquad \text{(eqn 4.3)}$$

Solving equation 4.3 for L yields
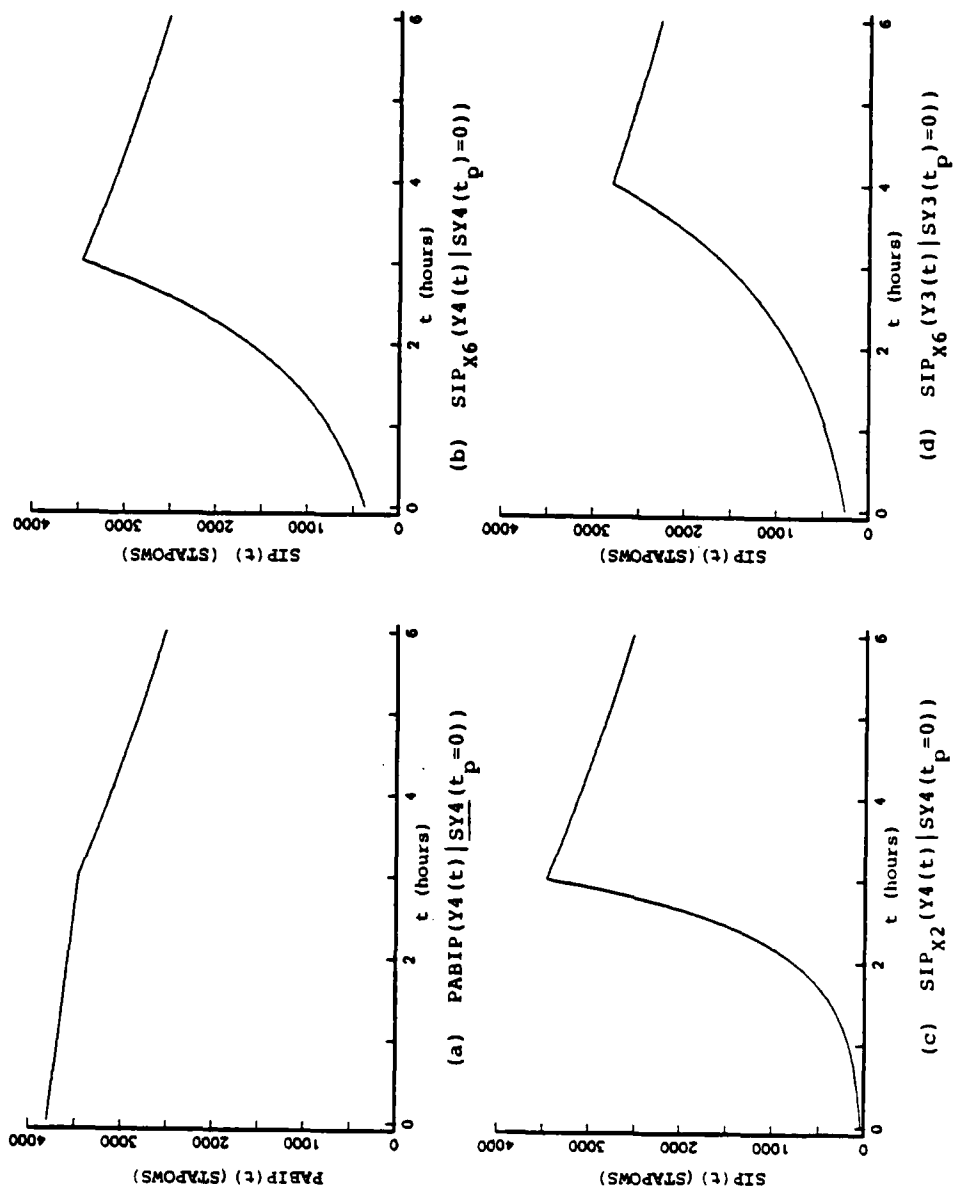
$$L = -\ln(0.97) = 0.0304592$$

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Figure 4.5.   Determination of SIP Curve for Y3 at t_p=0.

$$
SIP_{X_i}(t|t_p=0) = \begin{cases} PABIP_{X_i}(t_A|t_p=0) \times e^{-D(t_A-t)} & \text{for } t \le t_A \\ \\ PABIP_{X_i}(t|t_p=0) & \text{for } t > t_A \end{cases} \qquad \text{(eqn 4.9)}
$$

From Figure 4.4 it is estimated that Y4 entered the Brigade area of interest at $t=t_0=-1$. Thus the length of the Brigade area of interest is $(t_A-t_0)=(3-(-1))=4$ hours. Assuming that $SIP(t_0|t_p=0)=0.05\times SIP(t_A|t_p=0)$ the parameter, D, in equation 4.9 is computed (using equation B.6) by

$$
D = \frac{-\ln 0.05}{t_A-t_0} = \frac{2.9957323}{3-(-1)} = 0.748933 \qquad \text{(eqn 4.10)}
$$

Substituting the predicted variable values into equation 4.9 yields

$$
SIP_{X_6}(t|t_p=0) = \begin{cases} 3468\times\exp[-0.748933\times(3-t)] & \text{for } t \le 3 \\ \\ 3468\times\exp[-0.1053605\times(t-3)] & \text{for } 3 < t \le 6 \end{cases} \qquad \text{(eqn 4.11)}
$$

The graph of the function in equation 4.11 is shown in part (b) of Figure 4.5. The same procedure is used to determine the SIP of Y4 as predicted by Battalion X2. The only difference is that the time that Y4 is expected to enter X2's area of influence is $t=t_0=1$ (see Figure 4.2). Using the formula from equation B.6 yields

$$
D = \frac{-\ln 0.05}{t_A-t_0} = \frac{2.9957323}{3-1} = 1.4978661 \qquad \text{(eqn 4.12)}
$$

Thus

$$SIP_{X_2}(t|t_p=0) = \begin{cases} 3468 \times \exp[-1.4978661 \times (3-t)] & \text{for} \quad t \leq 3 \\ \\ 3468 \times \exp[-0.1053605 \times (t-3)] & \text{for} \quad 3 < t \leq 6 \end{cases} \quad \text{(eqn 4.13)}$$

The graph of the function in equation 4.13 is given in part (c) of Figure 4.5. For comparison purposes the SIP curve of Y3, from the Brigade perspective, is shown in part (d) of Figure 4.5. It appears from Figure 4.5 that Y3 is expected to arrive at time $t_A=4$ and to have $PABIP(Y3(t_A)|\underline{SY3}(t_p=0))=2800$. The expected arrival time is shown in Figure 4.4.

4. <u>SIP Curves For $t_p=0$</u>

The SIP curves for the present time $(t_p=0)$ for the Blue Brigade, X6; and the sectors for Battalion X1 and X2 are shown in Figure 4.6. For each of these Blue units, the SIP for the Red entities that are expected to be within that unit's area of influence is plotted as a solid line. Since the Blue units are in defensive positions, one STAPOW (Standard Power unit) of Blue forces is roughly equivalent to 3 STAPOWS of Red forces. Thus the dotted lines in Figure 4.6 actually represent 3×SIP of the Blue units. The Blue units that are included in a sector are only those units that are committed to a specific mission in that sector. At time $t_p=0$ the only Blue units that are committed are X1 to sector 1 and X2 to sector 2. (Parts (c) and (d) of Figure 4.6). The Brigades
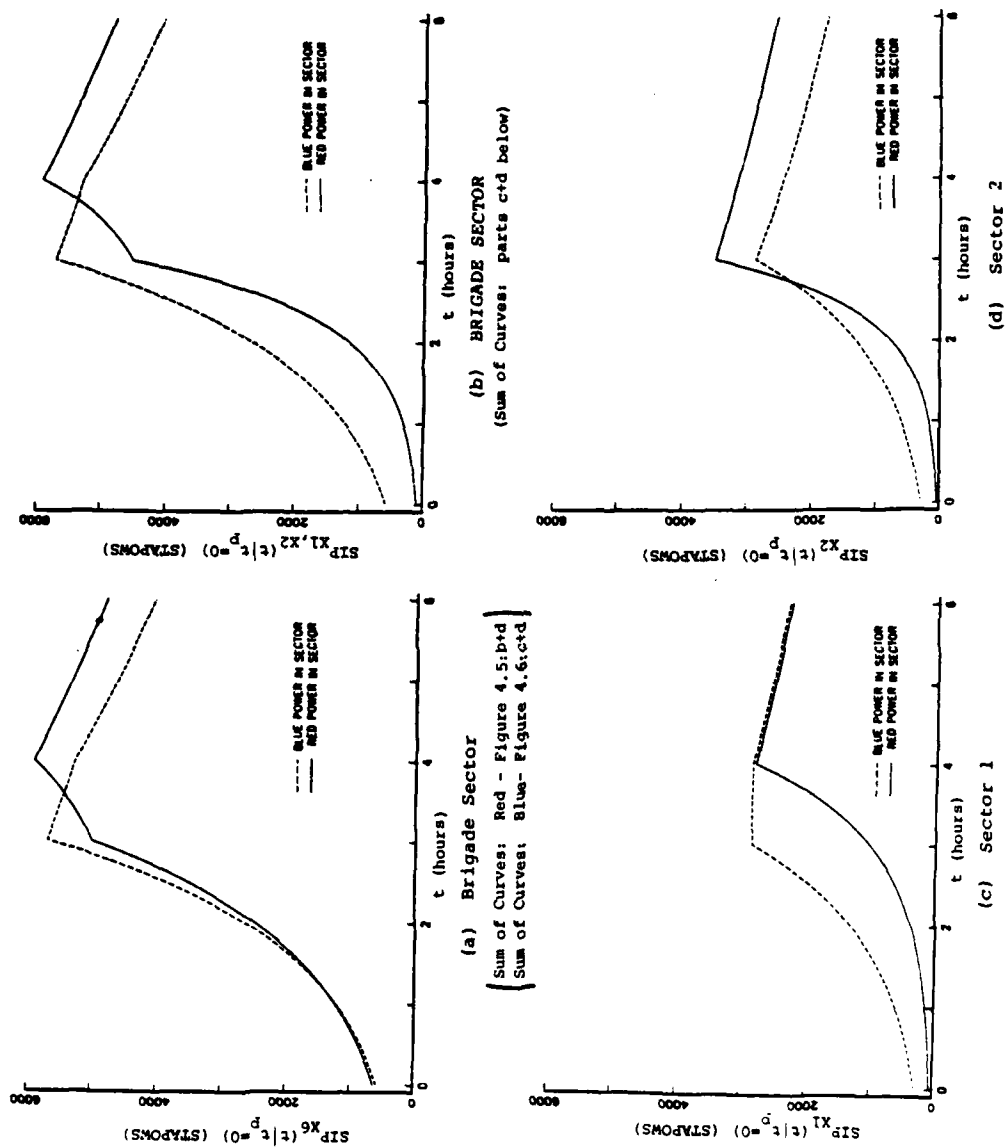
Figure 4.6

SIP Curves for Sectors at $t_p=0$.

sector includes both sectors 1 and 2 plus additional areas beyond these two sectors. Thus the power included in the Brigade sector (since X1 and X2 are the only Blue forces committed at $t_p=0$) is the sum of the powers of X1 and X2 which is shown in parts (a) and (b) of Figure 4.6. This implies that two simplifying assumptions have been made for this example. The first is that

$$SIP_{X1}(X1(t)|\underline{SX1}(t_p=0))=SIP_{X6}(X1(t)|\underline{SX1}(t_p=0)) \text{ and}$$

that

$$SIP_{X2}(X2(t)|\underline{SX2}(t_p=0))=SIP_{X6}(X2(t)|\underline{SX2}(t_p=0)) \ .$$

In other words the power of the Blue units is perceived to be the same by the Battalion and the Brigade levels of the hierarchy. The second is that there are no synergistic effects between entities X1 and X2. Neither of these assumptions are required in GVS and are made at this point only to simplify the example.

The Red power curves for the entities within the Brigade sector have different shapes in parts (a) and (b) of Fig. 4.6. For both parts (a) and (b) the assumption of no synergistic effects of the Red units is made. However, the other assumption that $SIP_{X1}(Y3(t)|\underline{SY3}(t_p=0))=SIP_{X6}(Y3(t)|\underline{SY3}(t_p=0))$ etc. is made only for part (b). The difference in the two curves is shown to emphasize the fact that the power of approaching entities is perceived differently by different levels

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of the hierarchy. One additional point worth mentioning is that the contributions of entities Y1 and Y2 to the Red SIP in the Brigade sector is very small. This is because intelligence reports expect Y1 and Y2 to wait for resupply and/or realloca- tion of their assets and then initiate continuation of the attack at approximately t=6. Thus even though Y1 and Y2 are close "distance-wise" they are actually quite far "time-wise" from the Blue Brigade.

For the remainder of the discussion the diagrams of the Brigade sector are to be interpreted as being the percep- tion of the Brigade. (e.g., as in part (a) of Figure 4.6).

There are many possible ways of using the SIP curves to determine when a decision needs to be made. The method used in this example is that if the power of the Red entities in a sec- tor is larger than three times the power of the Blue entities in a sector, a decision by a Blue level of the hierarchy is required.

5. First Decision Point

Consider parts (a), (c) and (d) of Figure 4.6. From part (a) the Brigade commander perceives that he has a problem at time t=0. However, after realizing that none of the Red entities will be in position until time t=3, the Brigade com- mander determines that even though he has less power than the enemy over the interval (0,1.2) he does not have to allocate additional assets because the situation improves to acceptable levels before the enemy arrives. The next point where a decision has to be made according to the Brigade sector curves
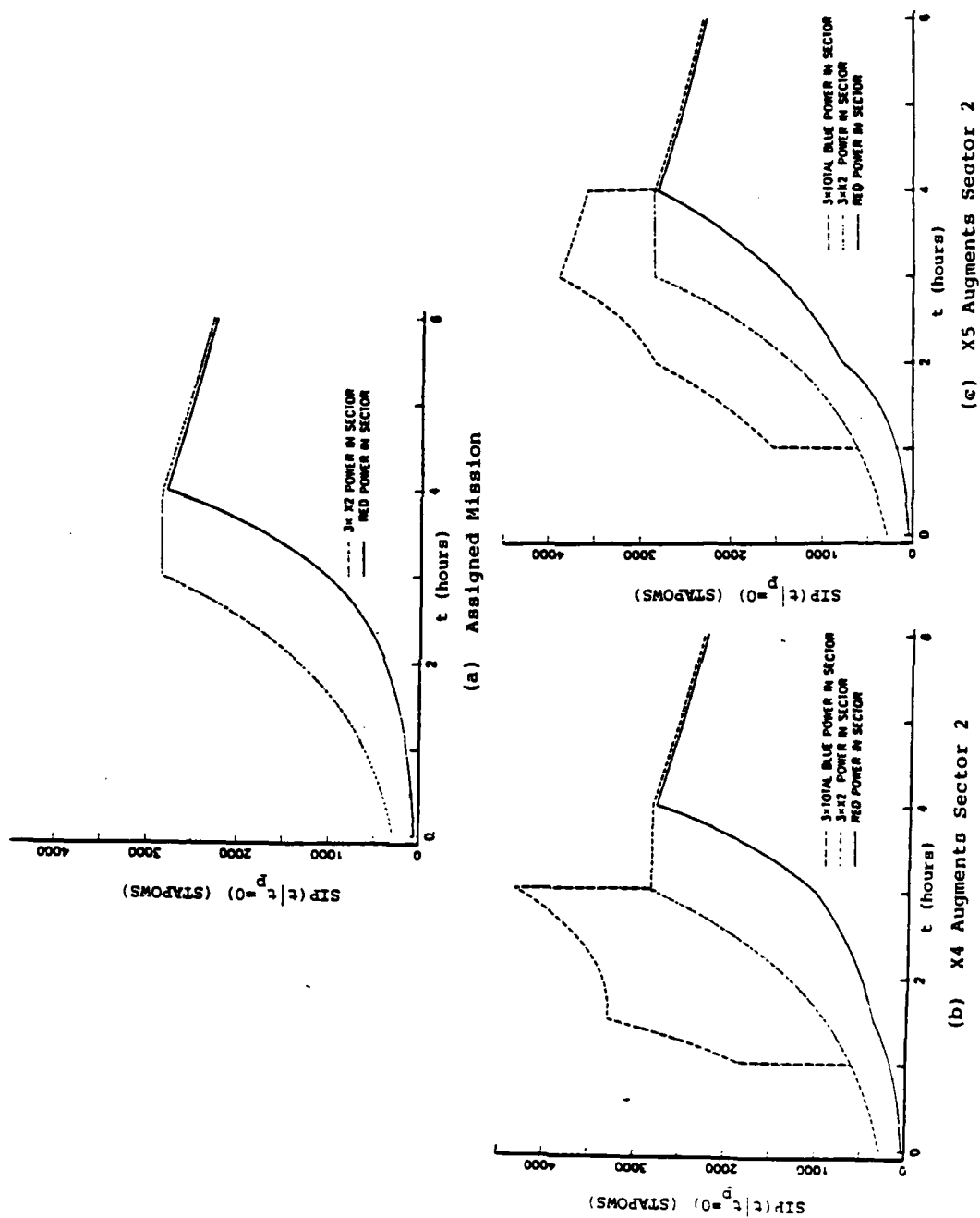
Figure 4.7.   SIP Curves for First Decision (at $t_p = 0$).

is at time t=3.5. However, the Battalion commander for X2 informs the Brigade that he will need assistance in sector 2 no later than t=2.8 (see part (d) of Figure 4.6) After considering the sector 2 power curves, the Brigade commander agrees that X2 needs assistance. If the Brigade committed either X3, X4 or X5 to sector 2 for the entire time period from t=0

to t=6 then sector 2 would have enough power to handle Y4. (That is, the power curve of the Blue forces in sector 2 would exceed that of the Red forces in sector 2 from t=0 to t=6.) However, since it is early in the battle (the Brigade has to hold until at least t=8) the Brigade commander wants whatever asset that supports X2 to be released from that commitment no later than t=4. Therefore the only option that the Brigade commander has is to use one of his reserve assets (X3, X4 or X5) to translate the power curve of Y4 so that it will be below that of X2 for $t \geq 4$ in Figure 4.6(d). As was shown in Figure 3.3 the power curve of a Red entity can be shifted to the right by delay, down toward the abscissa by attrition or down and to the right by a combination of attrition and delay.

In this instance the Brigade commander decides to try for a combination of attrition and delay as shown in Figure 4.7(a). The required level of effectiveness is given by the solid line in Figure 4.7(a) for $t > 4$. Thus a successful mission would be one that resulted in the power of Y4 falling at or below this line for $t > 4$.

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The Field Artillery and Helicopter modules return the SIP curves that can accomplish the mission as shown in parts (b) and (c) of Figure 4.7. Notice that the total amount of Blue power in the sector in parts (b) and (c) of Figure 4.7 includes the power of Battalion X2. (e.g., in Figure 4.7(b) the total power curve includes the helicopter unit, X4, and Battalion X2.) The ground manuever module determines that it is infeasible to use X3 to accomplish the desired mission. The decision that the Brigade commander must make is whether to use field artillery or helicopters. The possibility of the joint use of these assets is beyond the scope of this example. The power that these two entities contribute to sector 2 in order to accomplish the mission are shown in parts (a) and (b) of Figure 4.8. The area under the curves are equal, indicating that the quantity of each asset was chosen to realize the given level of effectiveness dictated by the mission. The value curves for these assets are shown in parts (c) and (d) of Figure 4.8. These curves were generated using the algorithm described in section D2 of Chapter 3. The value of G=-2 in equation 3.12 was used for each asset. For equation 3.16 the value for (DP/CP) for X4 was (DP/CP)=1.5 and for X5 was (DP/CP)=1. In this case the area under the value curve for the field artillery (X5) is smaller than that for the helicopters (X4). Therefore the Brigade commander's decision is to use X5, since it achieves the desired level of effectiveness at the smallest cost. Here the area under the value curve is
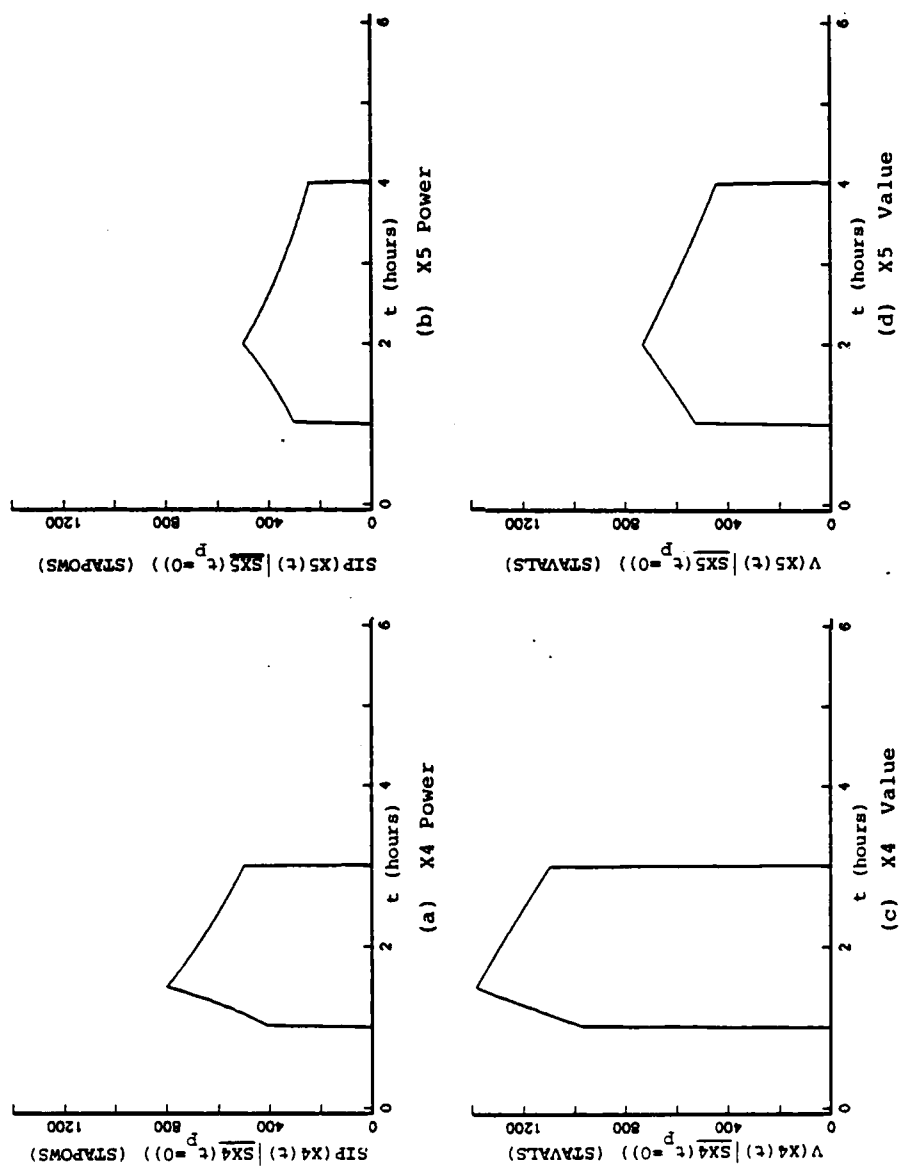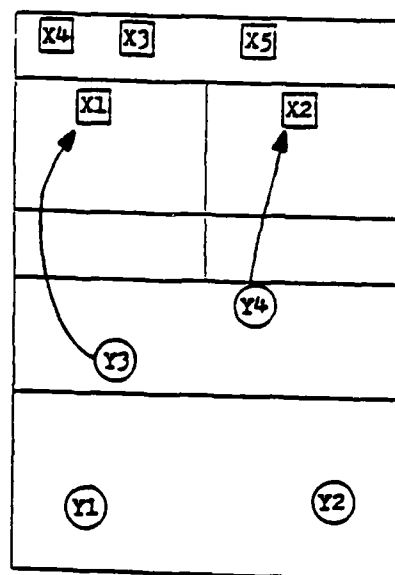
Figure 4.8

Power and Value for Alternative Assets for First Decision.

considered a type of lost opportunity cost. If the entity is used for this mission, then it will not be available for other missions during this time.

In addition to the evaluation of the value and power curves associated with using X4 and X5 against Y4, the Brigade commander is also informed of the latest time by which the entity must be ordered to do the mission (assumed to be time   t=1 for both X4 and X5). Thus the decision is made to order X5 to prosecute Y4 as a target, with feasibility and requirement checks to be performed at t=1. If the latest time for order execution was t=2.5, the Brigade commander might give warning orders at time t=0 to X5 but withhold the execution order until t=2.5 to be sure the situation had not changed enough by then to alter the choice of the asset for the mission or even the need to do the mission at all.

The position of the forces at time, $t_p=1$, is shown in part (a) of Figure 4.9. The notation used in the figure is that when the present time is t_p, the condition that exists (or is expected to exist) at time, t, is shown in the accompaning schematic. Thus part (a) is the condition at time, t=1, and part (c) is situation that is expected, at time, $t_p=2$, to exist at time, t=3. As can be seen in part (a) of Figure 4.9, the situation has not changed from what was expected at time $t_p=0$ (see Figure 4.4). Thus X5 is ordered at t=1 to augment the Blue power in sector 2 and to prepare to prosecute the target, Y4.
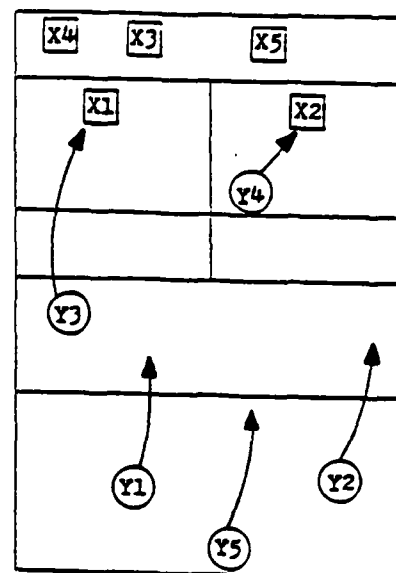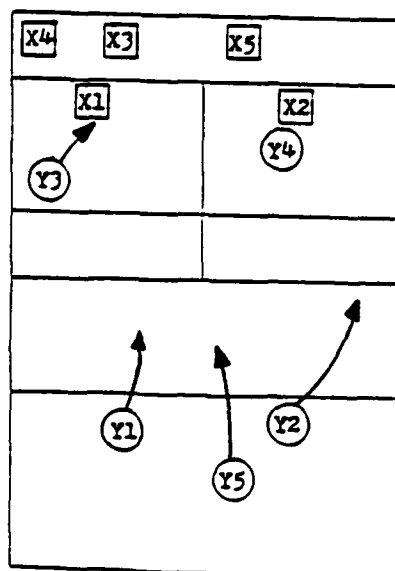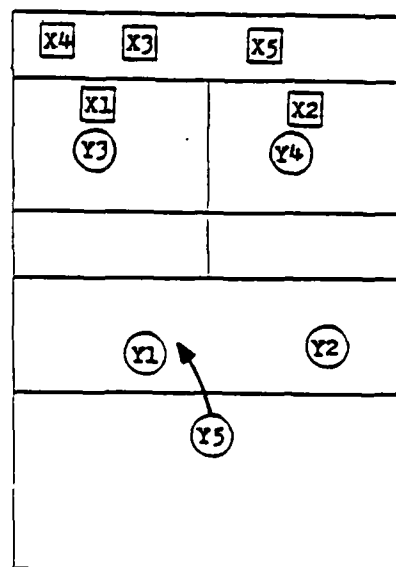
Figure 4.9.   Position of Forces for $t_p=2$

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6.   Second Decision Point

In part (b) of Figure 4.9 the situation that actually exists at $t_p=2$ is different than what had been originally expected. As shown in parts (b), (c) and (d) of Figure 4.9 (which correspond to the situation at time, t=2, and the expected situation at t=3 and then t=4) Y1 and Y2 are not waiting until time, t=6, to begin moving again. In addition another Red entity, an ammunition convoy, is detected moving into the Brigade area of interest. The SIP curves for the Brigade sector (for $t_p=2$) are shown in part (a) of Figure 4.10. From these curves it is apparent that execution of whatever decision is made must occur no later than t=5.1. Examination of the SIP curves for sectors 1 and 2 (not shown) indicates that there are two possible strategies. Strategy A is to prosecute the Ammunition Convoy (Y5) by time t-5 and augment sector 1 by time t=7. Strategy B is to augment sector 1 by time t=5. It is important to notice that the development of possible Brigade strategies required the use not only of the Brigade sector SIP curves, but the Battalion sector SIP curves as well. Implicit in each strategy is the requirement to either reduce the power curve of the Red asset or to increase the power curve of the Blue assets by specified amounts. The functional modules determine the required notification times for each asset to accomplish the required level of effectiveness in each strategy. These times are shown in TABLE 4.

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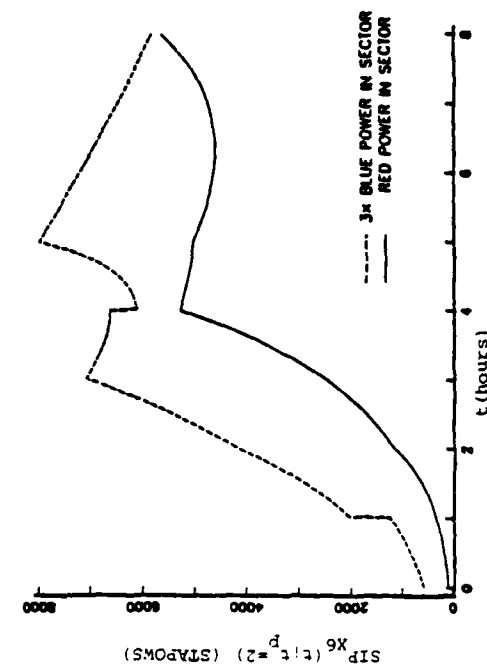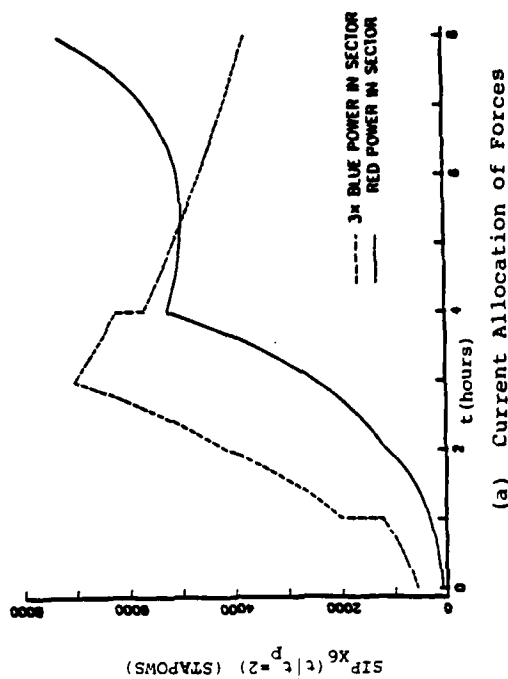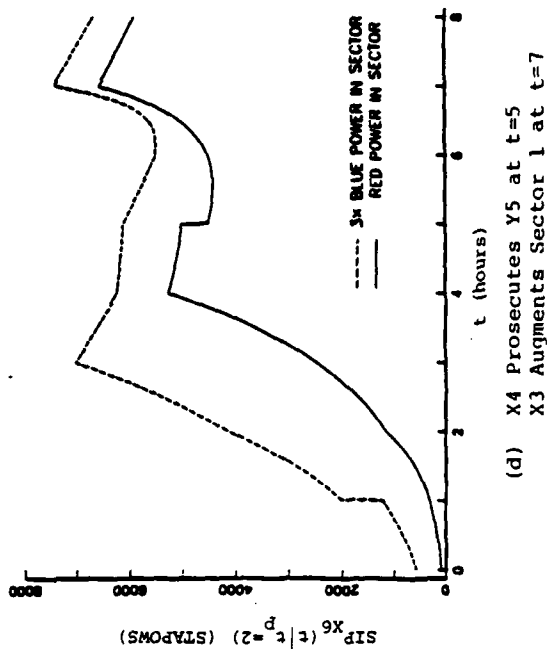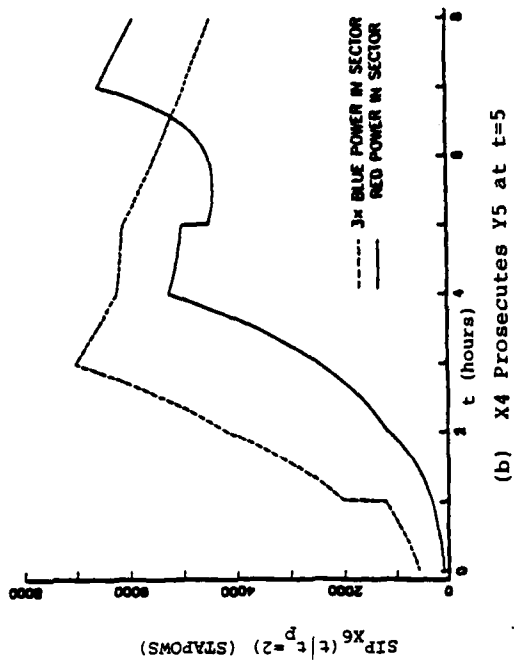
Figure 4.10. SIP Curves for Second Decision (at $t_p=2$)

TABLE 4

REQUIRED NOTIFICATION TIMES (t_n)
IN ORDER TO ACCOMPLISH THE SECOND MISSION

////////////////////	STRATEGY A		STRATEGY B
Entity	Prosecute Y5	Augment Sector 1 by t = 7	Augment Sector 1 by t = 4
X3 (Battalion)	$t_n = 0.0$	$t_n = 6.0$	$t_n = 3.0$
X4 (Helicopter	$t_n = 4.0$	$t_n = 6.5$	$t_n = 3.2$
X5 (Field Artillery)	$t_n = 4.5$	$t_n = 6.7$	$t_n = 3.5$

Since the present time is $t_p=2$, it is obvious that using X3 to prosecute Y5 is an infeasible option. If the Brigade commader wants to consider all possible plans for Strategy B then the decision must be made by t=3.0. If the decision is not made by t=3.5 then, unless the situation has changed by that time, the only option available to the commander would be Strategy A. Thus the Brigade commander decides to make his decision at t=3.0. Cutoff times and filters for information updating will have to be established in the model. Thus the commander making a decision at time, t=3.0, might use information that was available at t=2.5 (i.e., SIP curves for $t_p=2.5$).

As previously discussed (augmenting sector 2) the amount of power, SIP, (and the value of that power) that it takes to accomplish the mission is determined in the functional modules. Since each asset is being used to achieve a specified level of effectiveness, the SIP's of the assets (within a specific mission) should be the same. However, the value of

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those assets will probably be different. Suppose that the required level of effectiveness and the value of the assets used to accomplish that level of effectiveness are as shown in Table 5. One simple decision rule could be to choose the plan that achieves the maximum (Enemy Power Destroyed/Friendly Value Used) for the available strategies. There are cases where target priority may override the rule for using the maximum ratio to decide which target should be prosecuted by what asset. (e.g., final protective fires for an artillery unit, acquiring a nuclear battery as a target, etc.) It is realized that ratios eliminate consideration of the magnitudes of power and value. For this reason, additional filters that were not included in this example, would exist in ALARM for each hierarchical level.

For example, the Corps might have a list of targets with the following priorities and threshold ratios:

   (1)   Priority one: nuclear battery (1.0)

   (2)   Priority two: Army headquarters (1.5)

   (3)   Priority three: Division in an assembly area (2.0)

Thus if the Corps had acquired none of these targets the procedure would be that which is used in this example . If the Corps had acquired one or more of these targets it prosecutes the highest priority target with the assets that would be most effective against it. It would repeat this process until it had taken care of all of the targets on the priority list. At

TABLE 5

POWER AND VALUE OF ASSETS TO ACCOMPLISH MISSION

| | STRATEGY A | | | | STRATEGY B | |
| | Prosecute Y5 (Ammo) | | Augment Sector 1 | | Augment Sector 1 | |
Asset	Forecasted Red Power Destroyed	Value (Asset)	Forecasted Red Power Destroyed	Value (Asset)	Forecasted Red Power Destroyed	Value (Asset)
X3 (Battalion)	-	-	800	200	2000	600
X4 (Helicopter)	1200	300	800	500	2000	900
X5 (Field Artillery)	1200	700	800	800	2000	1000

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that time if there were any assets remaining the process would return to that described in this example.

The results for all possible plans are given in TABLE 6 assuming no special priority targets exist.

TABLE 6

POWER/VALUE RATIO COMPUTATIONS FOR VARIOUS PLANS

Plan	Strategy	Assets	Red Power Destroyed / Value (Assets Used)
1	A	X4 Prosecute Y5 and X3 Augment Sector 1	$\dfrac{1200+800}{300+200} = 4.00$
2	A	X4 Prosecute Y5 and X4 Augment Sector 1	$\dfrac{1200+200}{300+500} = 2.50$
3	A	X4 Prosecute Y5 and X5 Augment Sector 1	$\dfrac{1200+800}{300+800} = 1.82$
4	A	X5 Prosecute Y5 and X3 Augment Sector 1	$\dfrac{1200+500}{700+200} = 2.22$
5	A	X5 Prosecute Y5 and X4 Augment Sector 1	$\dfrac{1200+500}{700+500} = 1.18$
6	A	X5 Prosecute Y5 and X5 Augment Sector 1	$\dfrac{1200+800}{700+800} = 1.33$
7	B	X3 Augment Sector 1	$2000/600 = 3.33$
8	B	X4 Augment Sector 1	$2000/900 = 2.22$
9	B	X5 Augment Sector 1	$2000/1000 = 2.00$

Thus Plan 1 for Strategy A is chosen since it has the largest ratio of Red power destroyed to Blue value required to destroy it. The SIP curves for plan 1 are shown in Fig. 4.10(d). The schematics showing the location of entities for t=5,6,7,8 if plan 1 is used are shown in Fig. 4.11. If only the first part of Strategy A is implemented (X4 prosecutes Y5) the SIP curves are as given in Fig. 4.10(b). As can be seen in part (b) of Fig. 4.10 executing only the first part of Strategy A is not sufficient. The SIP curves for plan 7 (X3 augments sector 1, Strategy B) are shown in Figure 4.10(c) for purposes of comparison. The schematics that correspond to using plan 7 are shown in Figure 4.12.

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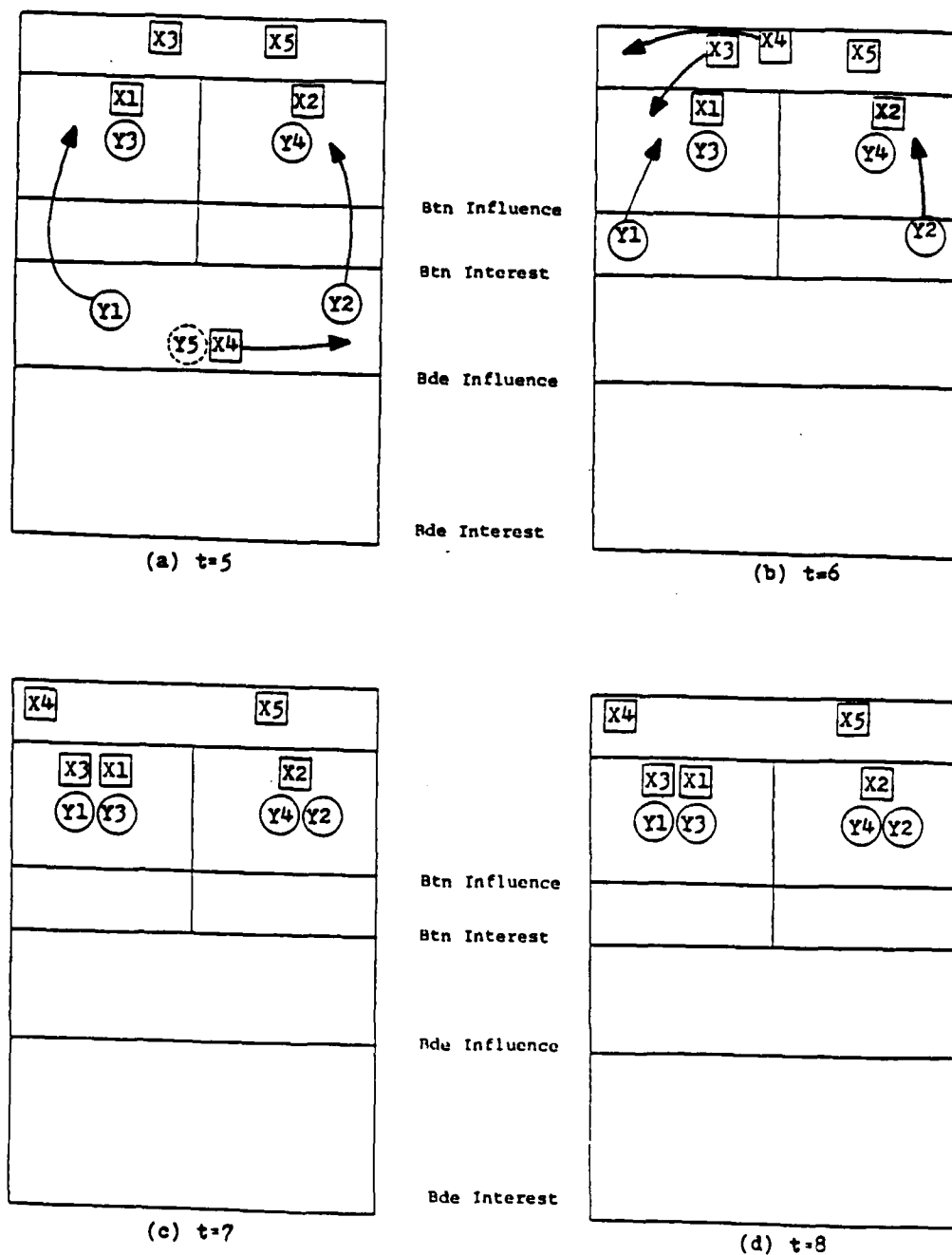
Figure 4.11. Position of Forces at $t_p=2$ for Plan 1

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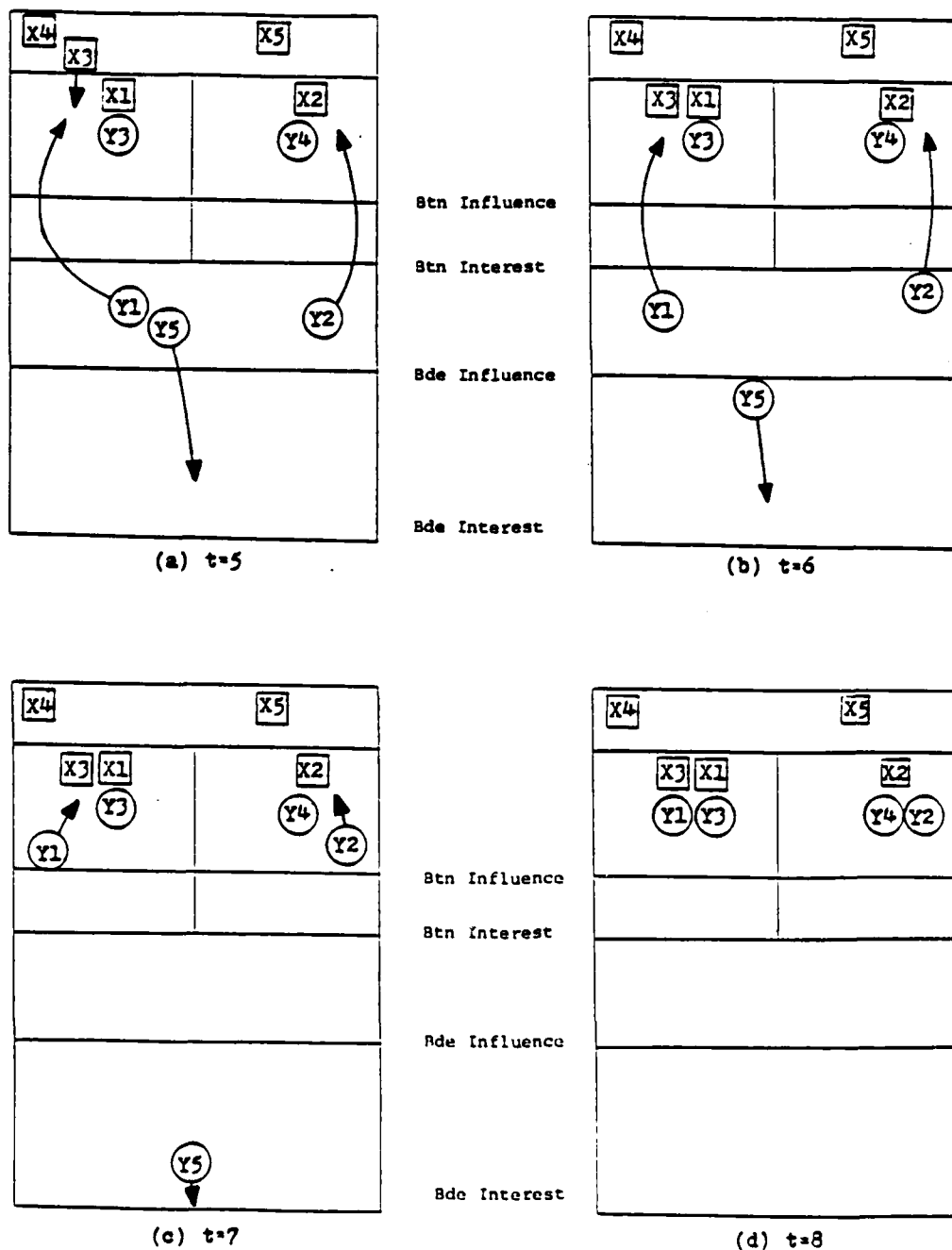
Figure 4.12. Position of Forces for $t_p = 2$ for Plan 7

Notice that if plan 1 is used (Figure 4.11) the arrival time for Y1 and Y2 is expected to be t=7. If plan 7 is used (Figure 4.12) the arrival time for Y1 and Y2 is expected to be t=8. The reasoning is that in plan 7, Y1 requires one hour for resupply and in plan 1 no resupply is conducted. It is assumed that Y1 and Y2 are conducting a coordinated attack and therefore are expected to arrive at the battle area at about the same time.

The Brigade commander decides to use plan 1. Since the required notification times (from Table 4.2) are $t_n=4.0$ for X4 and $t_n=6.0$ for X3 the Brigade commander decides to issue a warning order to X3 and X4 at t=2.0. At time t=4.0 the Brigade commander would make feasibility and requirements checks based on updated projections before assigning the mission to X4. Similar checks would be made before committing X3 at time t=6.0.

The purpose of this example was to demonstrate how the GVS could be used in some of the decision making processes within ALARM. In addition many facets of GVS were highlighted. A summary of the GVS and its applications is provided in the next chapter.

V. SUMMARY/FUTURE DIRECTIONS

A. SUMMARY

The Generalized Value System has been explicitly defined in this thesis. Several aspects of the system which show how it can be used to permit "future state decision making" were shown in the example in Chapter IV. The following are the key features of GVS as it has been developed in this thesis.

(1) It is assumed that the intelligence module will be able to predict the missions of the red entities that are detected. Once the expected Red missions are known the expected avenues of approach that the Red entities would use will be determined.

(2) For any given mission of an entity the requirement exists to be able to predict from the current conditions the power (SIP) that the entity is expected to have in the future. Derivation of SIP curves is shown in detail for one entity in Chapter IV.

(3) The exponential decay formulas assume a constant rate of advance (for SIP) and a constant loss rate (for PABIP). If these assumptions are not true then a transformation will be required from "simulation" time to "formula" time.

(4) The power (SIP) of an entity increases as the entity is closer in time (not necessarily distance) to performing its assigned mission.

(5) There is a difference in the perceptions, of the Brigade and Battalion commanders, of the power of an approaching enemy entity. This was illustrated by the difference in the SIP curves in Figure 4.4. Because of the differences in perception of enemy power this requires coordination between levels of the hierarchy. At the very least, the Brigade commander has to consider the power curves of the individual Battalion sectors as well as those for the total Brigades sector, in order to make decisions.

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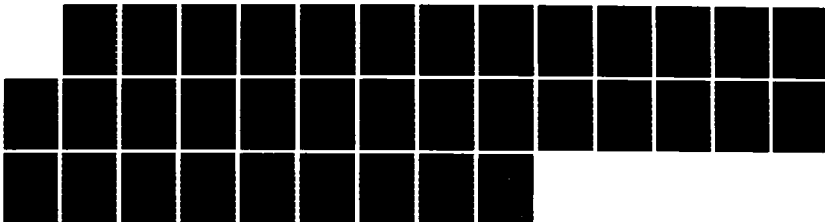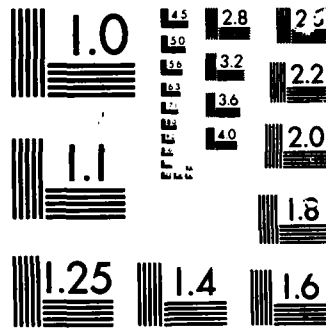MICROCOPY   CHART

(6) Power curves can be used to determine when a decision needs to be made, how much time can be spent gathering and evaluating information for the decision, and when a decision should be implemented. This was shown for target selection and target allocation decisions. It is felt that they can also be used for other required decisions such as logistics resupply, battle damage repair, communications support, etc.

(7) Functional modules are required to

    (a) Determine required notification times.

    (b) Determine if entities can perform a mission to the required level of effectiveness. (i.e., calculate SIP's for mission)

    (c) Determine the value of the entity that is to perform the mission (this could be the value that is expected to be lost or the value of the entire entity).

(8) One procedure that is used in the example to determine the need for a decision to be made is to multiply the power of the Blue units in a sector by 3 (since Blue is in defense and Red is on offense) and compare that power curve to the power curve of the enemy units that are in or are expected to be in that sector. Similar rules could be made for other missions (i.e., Blue offense and Red offense, etc.)

(9) There are basically two methods used to resolve a a problem when Red has more power than the Blue assets in a sector can handle. First, the sector could be augmented with additional units to increase the Blue power curve above the Red power curve. Secondly, the power curve of the enemy could be decreased by delay or attrition or a combination of both, so that when the additional support is withdrawn, the remaining Blue units would have sufficient power to handle the remaining Red units.

(10) The decisions that were made in this example were solutions to problems of the form minimize cost (value) subject to a given required level of effectiveness. The first decision involved finding the least valued asset to attack a single target. The second decision involved finding which asset should be used against multiple targets at different times.

(11) The derived power of an entity depends on how much the entity will increase the power of the entity it is supporting. This implies that supporting an entity that is engaged is more important than supporting an entity under identical conditions that is not engaged.

In summary, the Generalized Value System developed in this thesis provides procedures for quantifying the capability (power) and the importance (value) of entities on the battlefield. GVS is an improvement over the methodologies used in other combat models in that the power (and/or value) of non-combat entities (e.g., bridges, road junctions, etc.), combat support units and combat service support units, in addition to combat units, can be determined. Finally, these determinations are made as a continuous function of time, which provides the capability for future state decision making.

B. FUTURE DIRECTIONS

This thesis presents the initial research effort to represent decision making in the very complex environment of Airland Combat. There are several areas which require future research for continued development of the Generalized Value System. Other areas will be identified as the GVS is implemented and runs as an integral part of ALARM.

The possibility of using existing financial discounting and decision algorithms as tools for making decisions in ALARM should be explored. The field of economics has dealt with decision making in future time for many years. The procedures

that have been developed for various economic problems should be evaluated for their potential use within ALARM.

Quantification of the relationships between support and supported units will be required. Efforts should include at least the support areas of supply, maintenance, and communications.

An initial data base for the Basic Inherent Power of entities, as well as the various discount factors, must be developed. Several possible techniques for developing these inputs were discussed in this thesis.

Finally, the relationship between the value function as it is used in GVS and the value function as it is used in multiple objective decisions (specifically as it is defined by Keeney and Raiffa) should be explored. [Ref. 16: p. 80]

APPENDIX A

TERMINOLOGY AND DIMENSIONALITY OF VALUE AND POWER

1. VALUE

The word value can be used both as a noun and as a verb and can mean many different things. The following definitions are from a typical dictionary, the first eight are used as nouns and the last three are used as verbs. Value is defined as:

(a) attributed or relative worth, merit or usefulness

(b) monetary worth

(c) equivalent worth or return

(d) denomination, as of a monetary issue or postage stamp

(e) magnitude, quantity, number represented by a figure, symbol, or the like

(f) a point in the range of a function

(g) import, or meaning, as of a word or expression

(h) ideals, customs, institutions that arouse an emotional response for or against them, in a given society or a given person

(i) to consider with respect to worth, excellence, use-fulness or importance

(j) to regard or esteem highly

(k) to calculate or reckon the monetary value of. [Ref. 8: p. 1453]

The way value is used in this thesis is as given in definition (a).

It is appropriate, although entirely coincidental, that this thesis on the Generalized Value System is to be completed

in 1986. The theme for the U.S. Army for 1986, as determined by the Secretary of the Army and the Chief of Staff of the Army is "values" [Ref. 12:p. 1]. The way value is used in the theme for the U.S. Army is that given in definition (h). This is the way a psychologist or sociologist would use the word. Since the entire Army will, throughout 1986, be thinking, writing, or at least hearing about values as given in definition (h) a minor digression on this topic is appropriate.

Everyone has had experience with their society's value system. At this point the similarities between society's value system and the GVS, as perceived by the author, will be discussed. In this way any characteristics that an individual might transfer from their experience with society's value system to GVS would be done openly rather than subconsciously. A society's values are those that are generally accepted by the majority of people in the society. One characteristic of a society's value system is that even though the majority of people agree on what is important it is possible to group people into different categories based on how important certain things are to them. Everyone knows about the "generation gap". The values assigned to things tend to be different for young people, their parents, and their grandparents. This might be because their time horizons are different. Other categories that have apparently distinct values are poor, middle income, and rich people. People that are in the same situation (e.g., have no money or home) regardless of age tend to have the same values.

The observations about society's value system have counter-parts in the GVS. The values that are generally accepted by the majority of commanders could be those of the Corps commander. The "generation gap" in the GVS is between levels of command such as Battalion and Brigade. The time horizon and the types of problems that two battalions will have are usually more similar than for a battalion and its parent brigade. The "generation gap" probably is not very significant if there is a big difference between the situations that face the forces.

For instance suppose one brigade is involved in heavy combat and another is not even close to the enemy. Then the values of the brigade that is in contact will probably be closer to one of its subordinate Battalion's values than it would to the other Brigade's values.

None of these observations have been substantiated. They are only pointed out so that the reader will be aware that it is possible that they might subconsciously make these types of connections between their own personal experiences with their society's value system and the GVS. Only after GVS has been put into a working version of ALARM will it be possible to test these hypotheses. Until they have been proven they should be treated as assumptions about GVS.

Economics is another field, besides psychology and sociology, that has used the term value. Many different theories have been proposed in economics for defining and measuring value. Four of the most popular are:

(1) Utility theory states that the more uses an item
has the greater its value becomes

(2) Labor theory says that the amount of labor expended
in producing something is proportional to its value

(3) Cost theory equates the value of an item with the
cost of producing the item

(4) Price theory says that the price paid in exchange
for an object is a measure of its value.

Each of these theories has its own inconsistencies and in
the opinion of one economist:

1. Value is relative and is not an inherent feature of
anything.

2. Value can be measured only by comparison.

3. Value is the relationship between what someone wants
and what he is willing to give up in order to get it.
[Ref. 13: p. 35]

In the marketplace money is used to measure the value or
worth of an item. Through the interaction of supply and
demand for a given item, the price for that item is determined.
The price of an item could be considered its value. A dollar
can be used in trade because everyone accepts it and knows how
to determine the value of things (cars, food, etc.) in terms
of dollars. Thus dollars are an arbitrary but convenient and
accepted measure of value. (An ounce of gold or a standard
light bulb could also be used as money if they were accepted,
but they wouldn't be very convenient.) In combat, an arbitrary
but fixed measure of value could be dollars, a specific type of
tank or tank unit, a specific type of airplane or helicopter,
or even a specific type of supply such as fuel or ammunition.

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In physics an arbitrary but fixed measure is provided by the standard body, which is a cylinder of platinum that is carefully preserved in France [Ref: 14:p. 81]. Using the standard body, physicists can measure mass and force. In GVS the equivalent to the standard body is called a STAENT (standard entity). The STAENT is defined, somewhat arbitrarily, as an M1 tank Battalion in 1986 at 100% strength with a 3 day Basic Load of Supplies.

The name given to the measure of value in GVS is STAVAL (standard value). One STAVAL is defined as the value of one STAENT to a Blue Division commander when the Division (in defense) is facing a Red Army and the STAENT is on the FLOT in contact with an enemy Motorized Rifle regiment. Additional definitions will be required for the other levels of the hierarchy. It is realized that the definition of a standard body might be changed as a result of experiences gained through actual implementation of the GVS in ALARM. However, it is important that a fixed standard be established rather than allowing each user of ALARM to define their own standard body. The closest counterpart to value, as used in GVS, in the realm of physics is "weight".

2. POWER

The following are various definitions of power:

(a)   capability of doing or accomplishing something

(b)   the possession of control or command over others

(c)   strength; might; force

(d)   legal ability, capacity, or authority

(e)   a military force

(f)   work done or energy transferred per unit of time

(g)   the product obtained by multiplying a quantity by
      itself one or more times.   [Ref. 8:p. 1039]

Power of an entity as it is used in GVS is the ability of the
entity to change or influence enemy entities.   This coincides
with definition (a).   In physics, the closest term to the way
power is used in GVS is force.   Force is an influence on a body
or system, producing or tending to produce a change in movement,
shape or other effects.   [Ref. 8:p. 515]   The units of force are
Newtons ($\frac{1 kg \times meter}{Sec^2}$).   The Newton is defined as the amount of
force required to produce an acceleration of 1 meter per
second per second on the standard body.   [Ref. 14:p. 81]

It is unfortunate that power as used in physics is not the
counterpart of power as used in GVS.   As it stands force as
used in physics is the counterpart to power in GVS.   Since the
field of physics is not likely to change their definitions to
accomodate GVS the obvious answer is that GVS should use the
word force instead of power.   However, in combat, force means
a body of armed men, as in a task force.   Users would be put
in the difficult situation of determining the "force" (the
capability of an entity of the force (the organization).   Thus
the decision has been made to confuse the physicists rather
than to confuse the users of the model.

It is proposed that the power of an entity be measured in
terms of a STAPOW or standard power.   As was mentioned earlier

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the Newton in physics is defined in terms of influencing the standard body. The STAPOW will also be defined in terms of influencing the standard body of GVS, the STAENT. The problem is that there are many ways that a military unit can be influenced by other entities. Basically, however, there are three ways to influence enemy entities: destroy the physical assets, delay the physical assets, or disrupt the control or use of the assets (i.e., causing them to be used inefficiently). The effects on friendly entities would be the opposite of those for enemy entities. Definitions of STAPOW that correspond to the first two influences could be:

$$1 \text{ STAPOW} = 1 \text{ STAENT Destroyed per day} = \frac{\text{STAENT Destroyed}}{\text{day}}$$

$$1 \text{ STAPOW} = 1 \text{ STAENT} \times 1000 \text{ Meters/per hour} = \frac{\text{STAENT} \times \text{ KM}}{\text{hour}}$$

$$1 \text{ STAPOW} = 1 \text{ STAENT} \times 100 \text{ Meters per hour per hour}$$

$$= \text{STAENT} \times \frac{100 \text{ M}}{(\text{hour})^2}$$

Whatever is decided upon as the definition of STAPOW the other ways of influencing entities will have to be converted to that definition. This addresses the issue of attrition and manuever and their relative importance. Combining equations 3.18 and 3.22 the value of an entity, X1, at time, t, is given by

$$\text{Value}(X1(t)) = \frac{DP}{CP} \times \text{BIP}(X1) \times \left(\frac{1 - \exp^{[G \times \frac{\text{SIP}(X1(t))}{\text{BIP}(X1)}]}}{1 - \exp[G]} \right) \qquad (\text{eqn. A.1})$$

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Dimensional analysis of equation A.1 leads to the conclusion that

$$STAVAL = \frac{\%}{\%} \times STAPOW \times \left(\frac{STAPOW}{STAPOW}\right)$$

$$STAVAL = STAPOW .$$

Thus the value of an entity can be measured in standard power units.

APPENDIX B

MALTHUSIAN AND LOGISTIC POPULATION GROWTH MODELS

Suppose that Blue Brigade, X1, is determining the Situational Inherent Power $[SIP_{X1}(X1(t)|\underline{SY1}(t_p), \underline{SX1}(t_p)]$ of entity Y1 at time, t_p. In this appendix only one entity, X1, is determining the power of one other entity, Y1, at one point in time, t_p. Therefore notation 3c from Table 1 is used in this appendix. Thus $SIP_{X1}(Y1(t)|\underline{SY1}(t_p), \underline{SX1}(t_p)) = SIP(t)$.

Assume that a prediction of the amount of power that Y1 will have at time t_A (time when Y1 is expected to be in position to perform its mission) can be made at time $t_p(t_p < t_A)$, and that the power is $SIP(t_A)$. The amount of power that Y1 has in relation to brigade X1 when Y1 is outside of X1's area of influence is negligible. The amount of power that Y1 has when it is at the boundary of the area of influence (i.e., at time t_o) is subject to debate but it should be apparent that it is relatively small compared to the power that Y1 will have when it is in position to do its mission. Assume that the $SIP(t_o)$ is some small fixed percentage of $SIP(t_A)$. For illustrative purposes assume $SIP(t_o) = 0.05 \ SIP(t_A)$. Now, two points on the SIP curve are known. The next question to be asked is, what is the behavior of the curve between these two points (i.e., what is SIP(t) for $t_o < t < t_A$) ?

SIP(t) is the power of Y1 when it is $t_A - t$ minutes away from being in position to execute its mission. Defining

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t in this way, as opposed to a point in time in a simulation, makes it obvious that SIP should be a monotonically increasing function of t . Once formulas for SIP are obtained it will be necessary to convert the time in the formulas to simulation time. This will simply entail a reversal of the process that was used to estimate the time, t_A.

The problem that remains is to determine the type of monotomically increasing function of t that should be used to model SIP. Regardless of which function is chosen it should be relatively easy to compute and make intuitive sense.

1. LINEAR EQUATION

One simple representation is the linear function:

$$SIP(t) = \frac{SIP(t_A) - SIP(t_o)}{t_A - t_o} \times t + \frac{t_A \times SIP(t_o) - t_o SIP(t_A)}{t_A - t_o} .$$

While the linear function is monotonically increasing the rate of increase of power is a constant. Intuitively, however, the rate of increase should be small initially and should increase as the time approaches t_A. A commander would prefer to have a unit now rather than to possibly have it in the future. By having the unit for a longer period of time there would be more alternative uses of the unit. Also because of uncertainty there is a chance that the unit wouldn't arrive in the future. [Ref. 12:p. 209]   Therefore the power of assets that are to arrive in the future should be discounted to determine their power at the present time.

2. EXPONENTIAL EQUATION (MALTHUSIAN MODEL)

The assumption made in the original GVS paper is that the power of an entity before it is used is a discounted amount of the power that it will have when it is expected to be used. (The original paper actually talked about discounting value rather than power). The discounting that is proposed is a fixed percentage per time period or exponential decay. [Ref. 7:p. 3]

Equation 3.7 from Chapter 3 is

$$SIP(t|t_p) = PABIP(t_A|t_p) \times exp[-D(t_A-t)] \quad \text{for} \quad t \leq t_A \quad \text{(eqn B.1)}$$

Evaluating SIP at the time $t = t_A$ yields

$$SIP(t_A|t_p) = PABIP(t_A|t_p) \quad \text{(eqn B.2)}$$

Substituting from eqn B.2 into eqn B.1 and changing to the notation used in this appendix yields

$$SIP(t) = SIP(t_A) \times exp[-D(t_A-t)] \quad \text{for} \quad t \leq t_A \quad \text{(eqn B.3)}$$

So the further t is from t_A (i.e., the smaller t becomes) the larger the discount becomes and thus the smaller SIP(t) becomes. If it is assumed that

$$SIP(t_0) = 0.05 \times SIP(t_A) \quad \text{(eqn B.4)}$$

it is possible to compute the parameter, D . Evaluating
eqn B.3 at the point t_0 yields

$$SIP(t_0)=SIP(t_A) \times \exp[-D(t_A-t_0)] \qquad \text{(eqn B.5)}$$

Substituting from eqn B.4 into eqn B.5 gives

$$0.05 \; SIP(t_A)=SIP(t_A) \times \exp[-D(t_A-t_0)]$$

Dividing through by $SIP(t_A)$ gives

$$0.05 = \exp[-D(t_A-t_0)]$$
$$\ln \; 0.05 = -D(t_A-t_0)$$

Thus

$$D = \frac{-\ln \; 0.05}{t_A-t_0} \qquad \text{(eqn B.6)}$$

Since $-\ln \; 0.05$ is a positive number and (t_A-t_0) is also positive,
D will be a positive number.

If it is possible to discount power backward from
time, t_A, it is also possible to compound power forward from
time, t_0, as in equation B.7 .

$$SIP(t)=SIP(t_0) \times \exp[D(t-t_0)] \quad \text{for} \quad t \leq t_A \qquad \text{(eqn B.7)}$$

Two checks on equation B.7 can be made since SIP is
known for two points. For $t=t_0$ the result is obvious.
For $t=t_A$

$$SIP(t_A) = SIP(t_0) \times \exp[D(t_A-t_0)] \qquad \text{(eqn B.8)}$$

Substituting from equation B.6 into equation B.3 yields

$$SIP(t_A) = SIP(t_0) \times \exp\left[-\frac{\ln 0.05}{(t_A-t_0)}(t_A-t_0)\right]$$

This reduces to

$$SIP(t_A) = SIP(t_0) \times \exp\left[\ln_0\frac{1}{0.05}\right]$$

Then

$$SIP(t_A) = \frac{SIP(t_0)}{0.05} \qquad (eqn\ B.9)$$

Finally, substituting equation B.4 into equation B.9 yields

$$SIP(t_A) = \frac{0.05\ SIP(t_A)}{0.05} = SIP(t_A)$$

Thus the formula holds for $t = t_A$.

Equation 5, which predicts that power grows exponentially with time, is the same as the Malthusian model of population growth. [Ref. 10:p. 307] The Malthusian model (and also SIP) is based on the assumption that the average rate of change of the population (power) over an interval of time is proportional to the size of the population (power). Using the instantaneous rate of change to approximate the average rate of change leads to the formula

$$\frac{dSIP(t)}{dt} = k \times SIP(t) \text{ where k is a constant} \quad (eqn\ B.10)$$

When SIP(t) is known for a time, say t_0, the solution to equation (B.10) leads to equation (B.7) [Ref. 10:p. 306].

A graph of exponential growth using equation B.7 with SIP(t_0)=50, D=1, t_0=0 and t_A=4, is shown in Figure B.1. As can be seen in Figure B.1 the slope of the curve (over the interval (t_0, t_A)) is always increasing. Since

$$\frac{d^2(SIP(t))}{dt^2} = D^2 \; SIP(t_0) \times exp[D(t-t_0)]$$

is always positive, the rate of increase of SIP(t) is always increasing. For some types of entities, in particular large organizations such as Divisions, such a characteristic might not be appropriate.
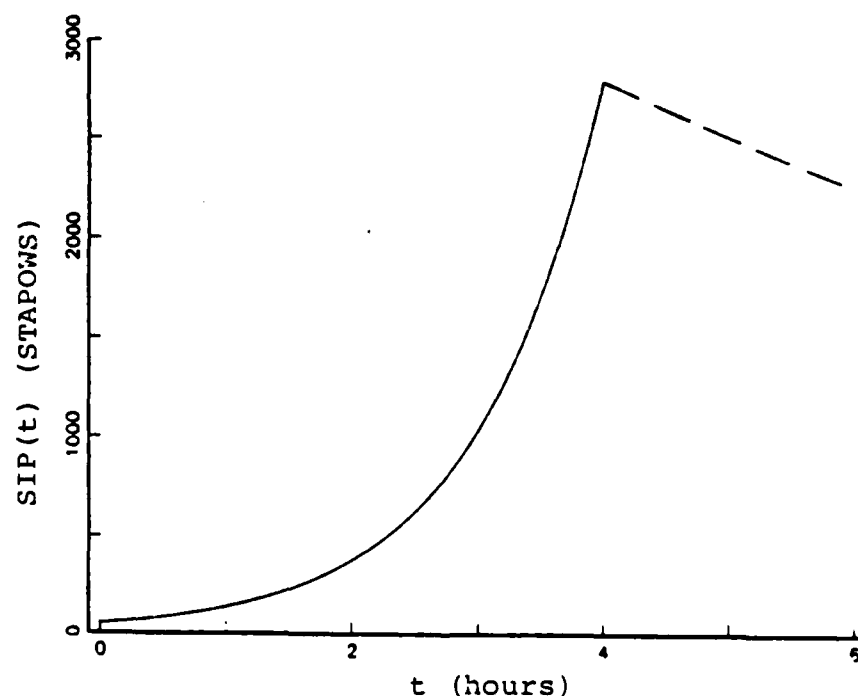

Figure B.1

Exponential Curve (Malthusian Growth Model)

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The dotted line after time, t_A, indicates attrition taking place. One problem (although not unsurmountable) is that SIP(t) is not differentiable at the time, t_A.

3. LOGISTICS EQUATION (LIMITED GROWTH)

An alternative to the exponential is the logistics growth model (also called limited growth model). This model is a refinement to the Malthusian model where it is assumed there is a finite limit to a populations size. Let M = maximum of SIP(t) $\forall t$. The logistics curve is defined in equation (B.11). [Ref. 10:p. 308]

$$SIP(t) = \frac{M \times SIP(t_0)}{SIP(t_0) + (M - SIP(t_0)) \exp[-D(t-t_0)]} \qquad \text{(eqn B.11)}$$

An example of the logistics curve for $t_0 = 0$, $SIP(t_0) = 50$, $t_A = 6$, $SIP(t_A) = M = 1000$, and $D = 1$ is shown in Figure B.2.

Obviously SIP(t) as defined in equation 11 will not achieve M at time, t_A, since it asymptotes to M at infinity. In equation B.12 the quantity $(M - SIP(t_A))$ is added to the right hand side of equation B.11 to obtain a modified Logistics Model.

$$SIP(t) = \frac{M \times SIP(t_0)}{SIP(t_0) + (M - SIP(t_0)) \times e^{-D(t-t_0)}} + M - \frac{M \times SIP(t_0)}{SIP(t_0) + (M - SIP(t_0)) \times e^{-D(t_A - t_0)}} \qquad \text{for } t_0 \le t \le t_A$$

$$= M \quad \text{for } t > t_A \qquad \text{(eqn. B.12)}$$

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Thus SIP(t_A) evaluated using equation B.12 is equal to M.
The graph of SIP(t) from equation B.12 is also shown in
Figure B.2. It can be shown that the rate of increase in
power reaches a maximum at the time, t, when (in equation B.11)
SIP(t) $=\frac{M}{2}$ [Ref. 10:p. 309]. Thus the rate of increase in
power starts out slowly, reaches a maximum and then decreases.

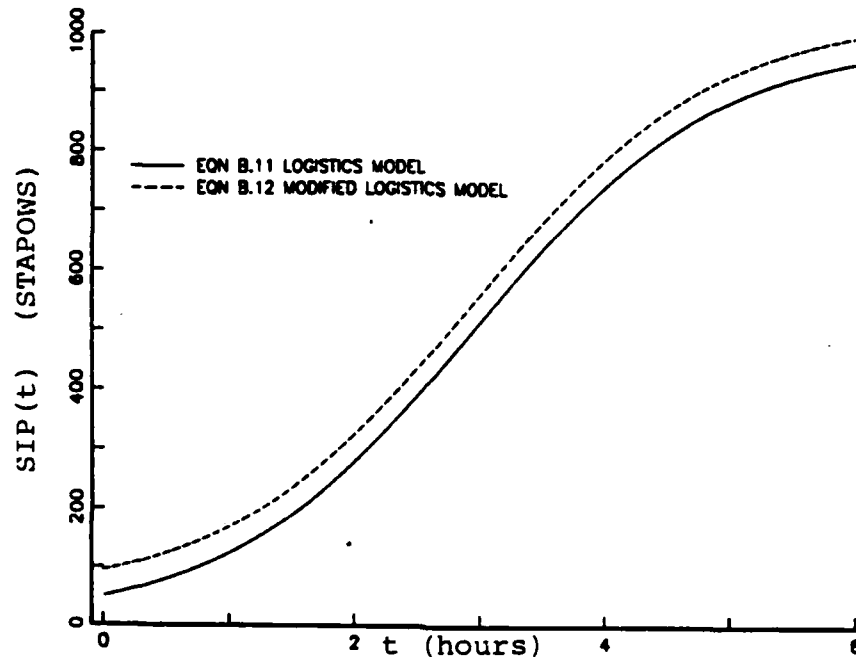Figure B.2
Logistics Curve (Limited Growth Model)

Equations B.11 and B.12 could be used to reflect
uncertainty about the actual arrival time. Each equation could
be used in a sensitivity analysis to determine how decisions
would change depending on which equation was used.

Each of the functions that have been considered (lin-
ear, Malthusian (exponential), and logistic) are monotonically

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increasing functions of time. Computationally the exponential and the linear equations are simpler than the logistic equations. Each function requires knowing t_0, $SIP(t_0)$, t_A and $SIP(t_A)$. The exponential and logistic equations have greater intuitive appeal than the linear equation, because the rate of increase changes as the entity gets closer to being used. Depending on the type of attrition that occurs after time, t_A, the logistic function may be differentiable at time, t_A. Thus there are advantages and disadvantages to each of the suggested ways of characterizing the power of an entity over the interval $[t_0, t_A]$. In this thesis the exponential growth equation B.7 or its corresponding exponential decay equation B.1 is used.

APPENDIX C

DERIVING POWER FOR LOGISTICAL UNITS

The following discussion is extracted from the original GVS paper. [Ref. 7:pp. 8-12] The only changes were to replace the word "value" by the word "power" and the symbol "V" by the symbol "PABIP". It is provided in its entirety because the original paper has not been published at this time.

As discussed above, the power of CS/CSS units must be derived from their effects on the power of the units they support. In this section, we present algorithms to compute the power for logistical units. Logistical units are the easiest of the CS/CSS units to evaluate since the functions of logistics in combat can be interpreted as a network of reservoirs (supply dumps) and pipes (transportation assets) whose function is to deliver a certain flow rate to the units in contact. Key parameters are the capacities of the reservoirs and pipes. The main purpose of the reservoirs is to function as "shock absorbers" in the face of fluctuating demands and replenishment rates, and in view of limited transportation capacity.

We would observe now that, in the absence of logistical support, the power of combat units, even when not in contact, decreases monotonically over time. This decay, which is depicted in Figure C.1, is of course due to the consumption of

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supplies, the wearout of equipment, and the nonbattle attrition
of personnel. The use of the term "decay" is deliberate, since
we would expect that, at least to a first approximation, this
decrease in power could be modeled either by

$$\text{ABIP } (\underline{s}(t)) = \text{ABIP}_O \ e^{-bt}, \text{ or } \quad \text{ABIP } (\underline{s}(t)) = \text{ABIP}_O \ e^{-bt^2} ,$$

where the value of b would depend on the unit's mission,
environment, etc. We also note that a fundamental assumption
of our model is that consumption, etc., that causes the change
in state which leads to this decay can be estimated for a
variety of conditions. This, of course, is really nothing more
than assuming the validity of consumption factors such as are
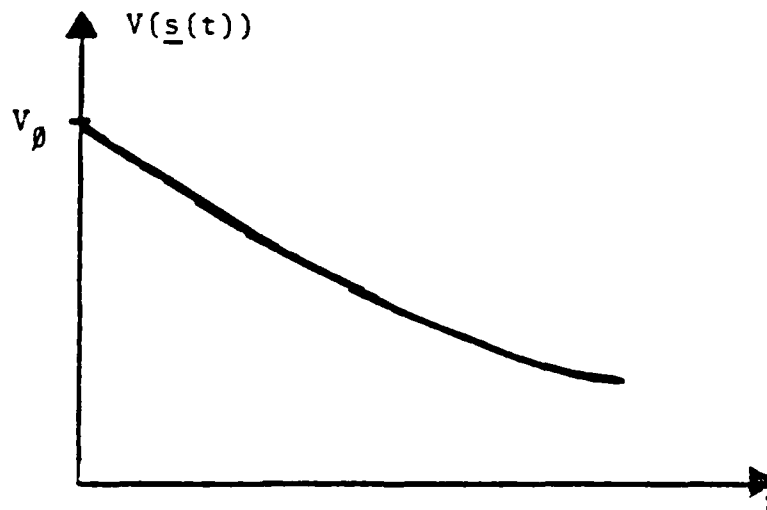found in manuals like FM 1Ø1-1Ø-1.

Figure C.1. Decay of Power

Logistical units act to change this decay in one of two
general ways:

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1. When the logistical unit is colocated with the supported unit, so that the support is immediately available, the effect will be to decrease the slope of the decay. This is indicated in Figure 2a (in theory, if the logistical unit had infinite support capacity, the decay curve would become flat.)

2. When the logistical unit is not colocated, then the support arrives at some time in the future. This will cause a discrete jump in the power of the supported unit at that time, following which the power will again decay until further support is received, etc. This behavior is shown in Figure C.2b.

ABIP($\underline{s}$(t))   ABIP(s(t))   ------Power with
                                                                  logistics
                                                            ――――Power without
                                                                  logistics

                    (a)   (b)
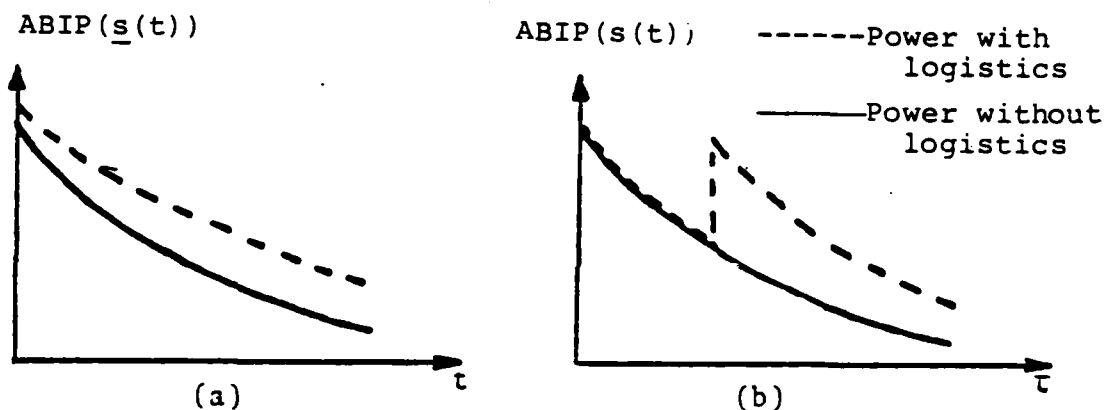
Figure C.2.   Power of Logistics

Lastly, we note that for logistical units, the average power is essentially an exponentially weighted average of the area between the two respective curves in Figure C.2.

Thus far, we have viewed logistics as a homogeneous mixture provided to the users. This, of course, is not very realistic. Ammunition is provided in a somewhat different manner than POL, for example, and the effect of ammunition resupply on a unit's

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power need not be the same as the effect of POL resupply. In addition, since the Airland model need not assume either side knows full ground truth on the other, we must also consider a procedure to assign power to a known logistical asset in the absence of knowledge about the location or condition of other assets. Thus we need to create an algorithm for determining the power of one specific type of logistic support, in the absence of full specific information on the other types. To do this, we first introduce the concept of the (logistics) state network.

The logistics state network is related to ideas of Markov processes, although the changes involved need not be random. Specifically, we assume that the state of a unit is given by an n-dimensional vector, and consider the possible changes that alter the unit's state from

$$S_1 = (a_1, a_2, \ldots, a_n)$$

to

$$S_2 = (b_1, b_2, \ldots, b_n) .$$

This transition will alter the power of the unit. We now propose a methodology to determine how much of this change to ascribe to the change from a_1 to b_1, from a_2 to b_2, etc.

The process begins by establishing a network of nodes and arcs, where the nodes are generated sequentially from the initial node, S_1. The immediate neighbors of this node correspond to those states that are reachable by changing

precisely one of the a_i to the corresponding b_i. The next
level is generated by those states that represent replacement
of precisely two of the a_i's, etc. Nodes are connected by an
arc if and only if the corresponding states differ in precisely
one position. The process continues until S_2 is reached. A
sample network for a three dimensional state vector is shown
in Figure C.3.
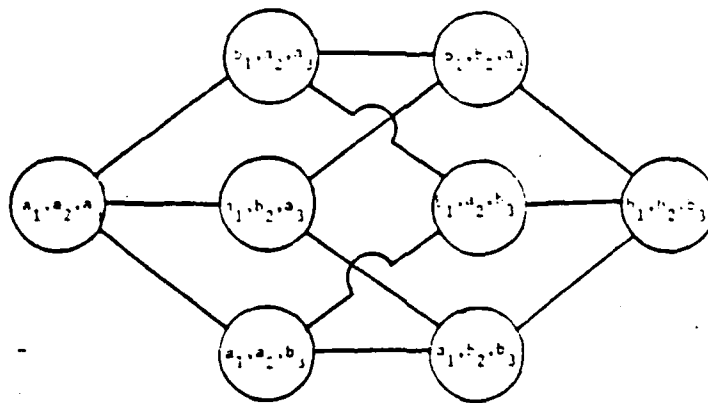
Figure C.3

Sample Network for a 3 Dimensional State Vector

Note that, in general, for every node at the ith level (where
$i=\emptyset$ corresponds to S_1), there will be precisely $(n-i)$ arcs
to the next level. Furthermore, there will be exactly $n!$
different paths from S_1 to S_2, and, for each component of
the state vector, there will be exactly one arc on each path
which represents changes due to that component. Each node rep-
resents some intermediate state between S_1 and S_2, with a
corresponding value somewhere between $ABIP(S_1)$ and $ABIP(S_2)$.

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The power assigned to any arc will be the difference between
the powers of the nodes at the ends of the arc. Then, finally,
we can compute the power of each component as the average of
the powers along all paths of arcs corresponding to a change
of that component. (Note this will involve multiple counting
of some arcs, when that arc occurs on more than one path.) This
is displayed in Figure C.4, where the powers of each of the
nodes is written above that node, and similarly for the powers
of the arcs. We would lastly note that, if desired, the simple
average could be replaced by a weighted average in the presence
of additional information about the probability of certain
intermediate states being actually reached, e.g., if a known
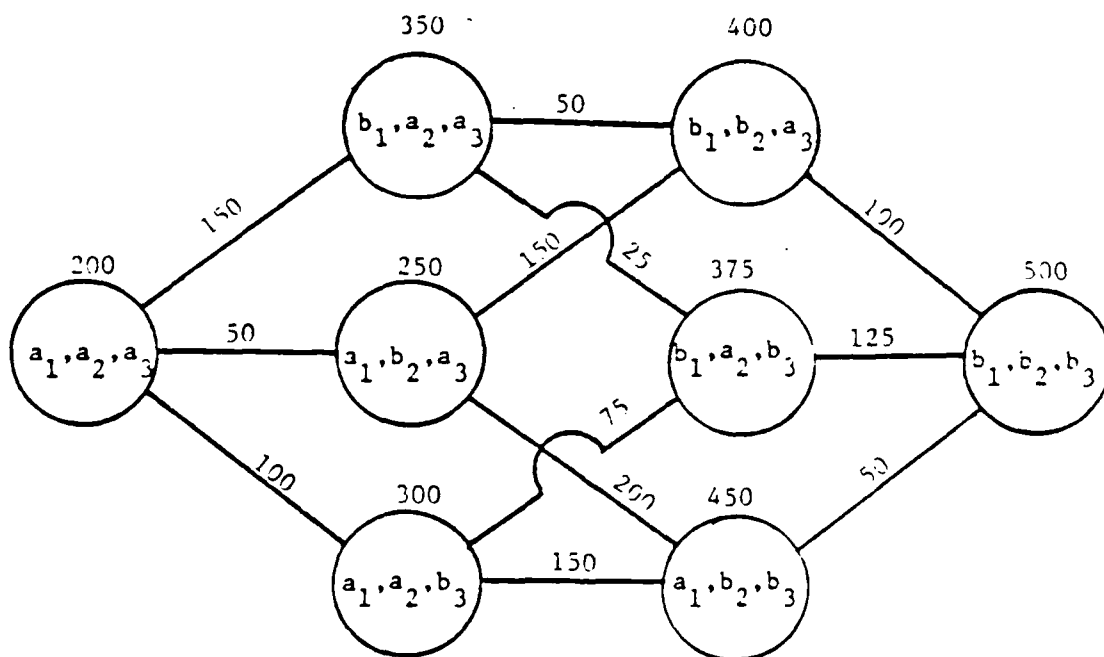POL shortage exists. [Ref. 7:pp. 8-12]

Figure C.4

Computing Power Using the Sample Network

ALPHABETICAL LISTING OF TERMS AND ABBREVIATIONS

1. ABDP - The Adjusted Basic Derived Power $ABDP(X1(t)|\underline{SX1}(t_p))$ of entity $X1$ is the Basic Derived Power of $X1$ adjusted for its current capability at time, t_p.

2. ABIP - The Adjusted Basic Inherent Power $ABIP(\underline{SX1}(t))$ of entity $X1$ at time, t, is the BIP of $X1$ adjusted for the specific mission and condition of the entity at time, t .

3. BDP - The Basic Derived Power, $BDP(X1(t)|\underline{SX1}(t_p))$ of entity $X1$ is the derived power that $X1$ would have if $X1$ (at full strength) was in position at time, t, to either increase or maintain the power of another friendly entity.

4. BIP - The Basic Inherent Power $BIP(X1)$ is the inherent power possessed by entity $X1$ at full strength, when it is in position to engage its most likely adversary as a direct result of $X1$'s ability to conduct combat operations.

5. CP - The current proportion of an entity of type A is the proportion of the entire force, at a specific point in time, t_p, that is of type A .

6. DP - The desired proportion of an entity of type A is the proportion of the entire force that a commander would prefer to have as type A for a given mission.

7. Derived Power - The derived power of an entity is that power it possesses because of its ability to influence

the states of other friendly entities or of entities that its forces are planning to use.

8. Entity - An entity is an object that is assigned power (and possibly value).

9. Inherent Power - The inherent power of an entity is its ability to directly affect the states of enemy entities or of entities that the enemy is using or planning to use (e.g., a bridge).

10. Object - An object is anything that is explicitly represented in the model.

11. Power - The power of an entity determined by a particular hierarchical level is its ability to change or influence either directly or indirectly the states of entities that the level will face that belong to the enemy or that the enemy is planning to use.

12. PBIP - The Predicted Adjusted Basic Inherent Power $PABIP(X1(t) \mid \underline{SX1}(t_p))$ of entity X1 at time, t_p, is the ABIP that X1 is predicted to have at time, t $(t > t_p)$.

13. SDP - The Situational Derived Power, $SDP(X1(t) \mid \underline{SX1}(t_p))$, of entity X1 is the ABDP of X1 decremented by an exponential factor based on the time interval before X1 can perform its mission.

14. SIP - The Situational Inherent Power, $SIP(X1(t) \mid \underline{SX1}(t_p))$, of entity X1 is the inherent power that X1 is predicted, at time, t_p, to have at time, t .

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15. STAENT - The STAENT (Standard Entity) is an M1 Tank
    Battalion in 1986 at 100% strength with a 3 day basic
    load of supplies.

16. STAPOW - STAPOWs (Standard Power) are the units of power.

17. STAVAL - STAVALs (Standard Value) are the units of value.

18. State - The state $\underline{SX1}$(t) of an entity X1 at time, t, is
    the condition of X1 at time, t, expressed as a vector
    of the entity's attributes.

19. Supply - The supply of an entity type is a measure of the
    quantity of that entity type that is on hand and available
    for commitment.

20. t_o - The time that an entity enters a given hierarchical
    level's area of interest.

21. t_A - The time that an entity is expected to be in position
    to accomplish its mission.

22. t_N - The time that an entity requires notification in
    order to be able to accomplish a specified mission.

23. t_p- The present time in the simulation (also can be thought
    of as the time at which predictions about future power and
    value are made.)

24. UV - Usefulness Value of an entity is the measure of how
    useful the entity is to the hierarchical level that is
    assigning the value. It includes long and short term
    usefulness.

25. V - The value of an entity to a particular hierarchical
    level at time, t, is the relative worth or importance of
    the entity to that level.

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